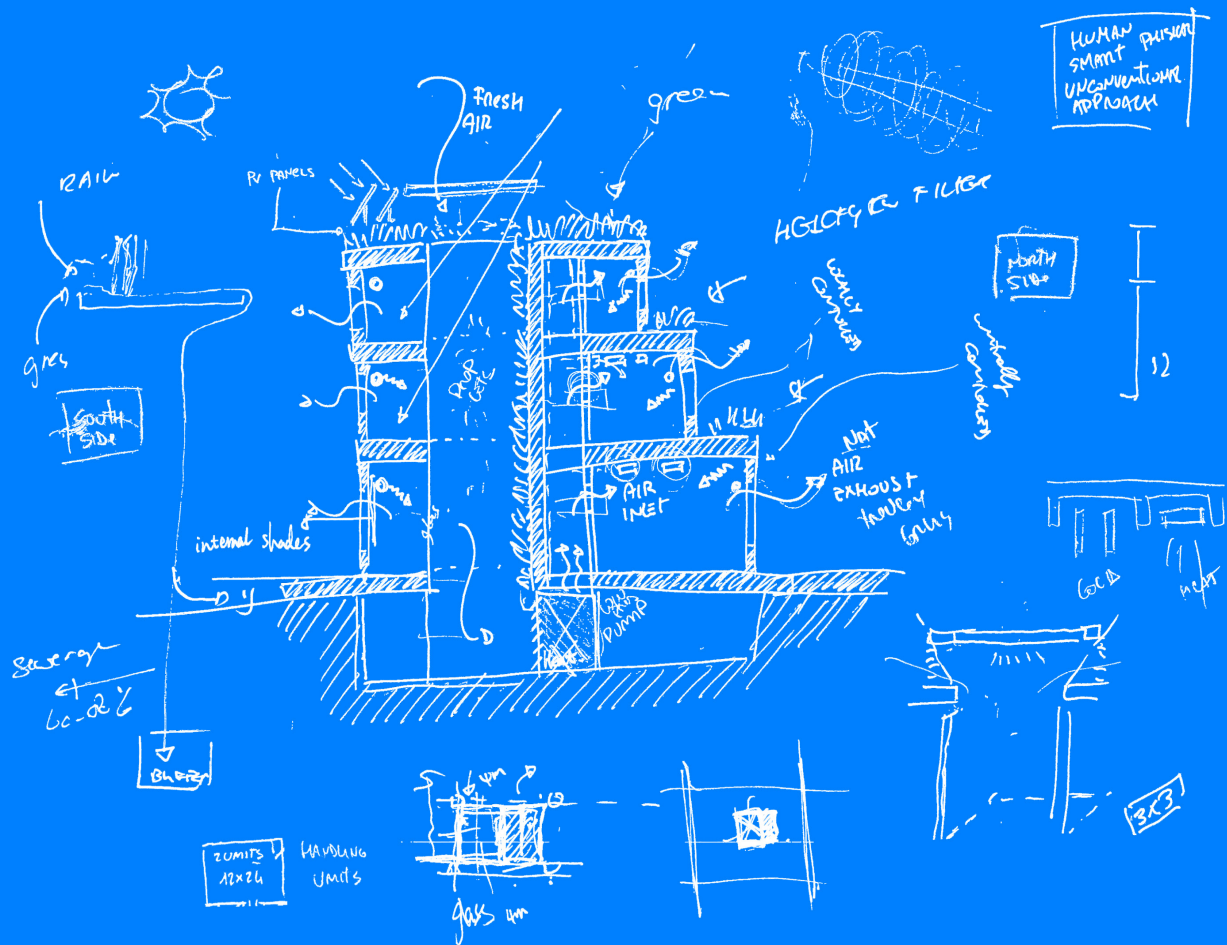


DESIGNING BUILDINGS WITH LOW-PRESSURE VENTILATION SYSTEMS



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Preface

September 2022

Ventilation is a big part of the energy consumption in buildings. Going towards a carbon neutral built environment, it is important to reduce the energy consumption of buildings and therefore also the ventilation energy. On the other hand ventilation is crucial in creating healthy and comfortable buildings.

Apart from the energy spent for heating, cooling and (de) humidifying the supply air, the biggest part of the energy usage for ventilation is what the central fan consumes for creating enough pressure to get fresh air through the building. Low-pressure ventilation is the key to reduce energy consumption. Nowadays mechanical ventilation systems are often designed with a standard approach, without considering site-related opportunities or needs, let alone alternative strategies, technologies and architectural integration. This leads to oversized or even unnecessary components and results in unesthetic additions to the architectural design and high energy consumption.

We see low-pressure ventilation as the opportunity to make an integral, sustainable design. Together with the architect we design a ventilation concept based on the site, building usage and architectural vision. The different components are an integrated part of the design. With this approach we give ventilation the space that it needs for optimal performance with minimal energy consumption.

The objective of this publication is to offer a compendium of many viable design solutions for reducing the fan energy in ventilation systems of new and existing buildings. We want to provide a brief and inspirational handbook for different kinds of professionals in the building industry, also without prior knowledge of ventilation systems.

The text is addressed to architects, designers, engineers and real-estate developers who want to know more about the topic of low-pressure ventilation. This booklet is the result of a collaboration between ABT and the Faculty of Applied Engineering and Design Sciences of University of Antwerp. We hope that by disseminating this information, the design of low-pressure systems will become common practice and together we will work on integrated, healthy and sustainable buildings.

Special thanks goes to dr. Ben Bronsema and Prof. Ulrich Knaack.

Introduction

01

While the **energy consumption** for heating, cooling and lighting becomes smaller every year, the electric energy use for fans hardly shows any reduction and becomes a dominant factor in the total energy use of these buildings.

For reaching **energy neutrality**, the fan energy consumption must be drastically reduced.

Low-pressure ventilation systems are the solution!”

01 | Introduction

Designing buildings with low-pressure ventilation systems can lead to large energy savings. However, the practice seems unknown to many professionals, both in the field of architectural design, engineering and construction. The reason does not only lie in financial arguments, but is based in a much broader range of barriers. Of course, the unfamiliarity and knowledge gap of how to design low-pressure systems is a relevant stumbling block, but also the “wish to control” the air flow, the IAQ and the comfort conditions results in installations that are fully equipped. All kinds of provisions are foreseen that filter, heat, cool, humidify, recover the heat and control the air. And this ends up in the well-known high-pressure system, that needs to be equipped with big fans to provide the air in the right places.

On the other hand, architects are often oblivious of the importance of integrating ventilation strategies in the design of the building itself and exploiting local climate related opportunities. To come to a serious reduction in fan energy for ventilation, the above described circle has to be broken.

During the last decades big steps have been made towards designing and realising energy neutral buildings. Due to the increased energy performance requirements, all kinds of energy saving technologies have been developed and implemented in the design and construction of new buildings. The list of developments that are relatively new is long and ranges from improved insulation

materials and high-performance glazing to LED lighting, all kinds of heat recovery systems and improved heat and cold generation appliances. Also in the field of ventilation substantial progress has been made compared to the situation of a couple of decades ago, e.g. the improved air tightness of buildings and systems, the development of heat recovery systems for ventilation and the development of demand-controlled ventilation (based on sensor technologies) has led to a substantial energy reduction.

Despite the large list of developments and improvements of energy saving technologies, we see specifically for the larger non-residential buildings that the electric energy use for fans hardly showed any reduction and becomes a dominant factor in the total energy use of these buildings. The average fan energy consumption is estimated as approximately 15-20% of the total building related energy [21], but other sources in literature propose even higher values, such as 30-40% [8].

This booklet offers a series of design solutions for reducing the fan energy in ventilation systems of new and existing buildings. The intention is to help designers, engineers and installers in daily practice pick up the (new) knowledge and see alternatives to the well-known traditional way of designing and realizing add-on mechanical ventilation systems with little to no architectural integration.



Three main solutions can be identified for achieving a low-pressure ventilation system:

- 1) improved mechanical ventilation systems
- 2) hybrid systems
- 3) natural ventilation systems.

The first consist of conventional ventilation systems, which are 100% mechanical and make use of traditional fans; however, each component of the systems is designed in order to minimize the flow resistance, advanced control techniques are used or alternative methods for distributing the air in the building. The second ones are mixed-mode systems which make use of both natural and mechanical ventilation, with a consequent reduction of the fan energy. The third are systems which fully rely on natural forces and do not make use of a fan.

The present booklet will focus on the first two approaches and will not treat fully natural ventilation. The objective is to provide design advices on how to reduce the fan

energy in traditional and hybrid ventilation systems and to show how the problem can be addressed with a holistic design approach, integrating low-pressure systems in the building design.

Chapter 1 provides some general explanation of what the flow resistance is and how it affects the fan energy consumption. An introduction on methods for reducing the fan energy is provided, as well as a way to classify different mechanical and hybrid systems. The chapter ends with a description of the design philosophy and a series of real design examples.

Chapter 2 gives a brief technical description of the components of a traditional mechanical system.

Chapter 3 describes different ways to reduce the fan energy in mechanical systems.

Chapter 4 is focused on hybrid ventilation systems and the use of local natural forces.

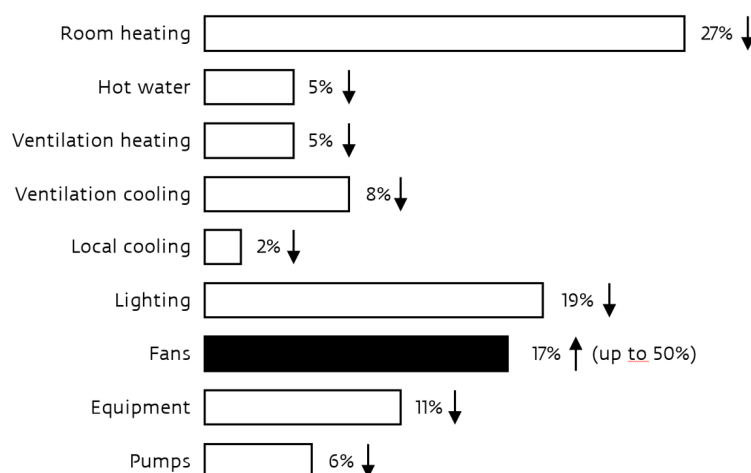


Figure 1. Energy consumption in large non-residential buildings

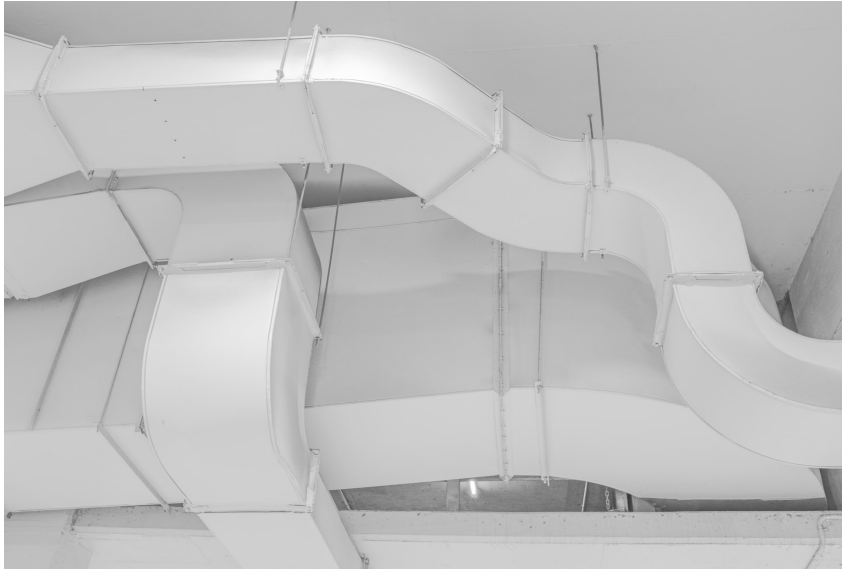




Figure 2. Examples of poor integration of the ventilation system with the building.

Pressure is the **driving force** of the flow.

Ducts with lots of obstacles, restrictions and curves have high flow resistance: the fan needs to increase the pressure in the system for overcoming the flow resistance, in turn consuming lots of energy.

In a **low-pressure system**, the flow resistance is minimised in order to reduce the fan energy consumption.



1.1 | Flow resistance and pressure difference

For understanding the basic principle of the motion of fluids such as air or water, one can think of a ball rolling on a surface. If the surface is smooth and free of obstacles, the ball can go very far just with a little kick. However, if the surface is bumpy and covered in grass, one might need to give the ball a stronger push in order to make it reach the same distance without losing momentum and stop. If the surface is covered in bushes and rocks, one needs to kick the ball very strongly in order to make it roll as far.

In a similar way, air needs a driving force (a kick) for flowing from a point to another: this driving force is in the form of a pressure difference. The more resistance the air encounters along its path, the higher this pressure difference between departure and destination must be for letting the air flow. As a matter of fact air, as any other fluid, spontaneously moves from a point at high pressure to another point at low pressure. When the path between these two points (for instance a pipe, an air duct or an opening in a wall) is large, smooth and free of obstacles, the air can flow with just a small pressure difference. On the contrary, when the path is narrow, rough and with several obstacles (e.g. restrictions, bends) the pressure difference must be larger in order to let the same amount of air move from the first to the second point.

In a similar way, one can think of the flow resistance as a dam obstructing the free flow of a river, making the water level rise upstream.

In the case of a building's conventional ventilation system, the pressure difference (the kick) is provided by a fan: the fan sucks the air from the external environment at atmospheric pressure and brings it to a higher pressure, so that it can flow through all the ductwork until the desired room, which is again at atmospheric conditions. For increasing the air pressure, the fan system consumes energy. In a poorly designed system, the ductwork can offer a very high resistance to the flow due to suboptimal sizing, an excessive number of bends and restrictions, deposited dirt, etc. In this case, the fan needs to increase the air pressure a lot, consuming a large amount of energy. On the other end, the ventilation system can be designed in order to offer as little resistance as possible, allowing the fan to consume less energy.

The concept of flow resistance, as described above, will appear several times in the present booklet. Often, it will also be referred to as pressure drop. In fact, each obstacle along the flow makes the pressure of air drop (like the ball which loses momentum over a bump); for this reason, although strictly speaking they are not the same thing, pressure drop and flow resistance can be used as synonyms for a given flow rate. The total pressure difference which needs to be provided to the air can be thought as the sum of the pressure drops caused by each obstacle along the flow.

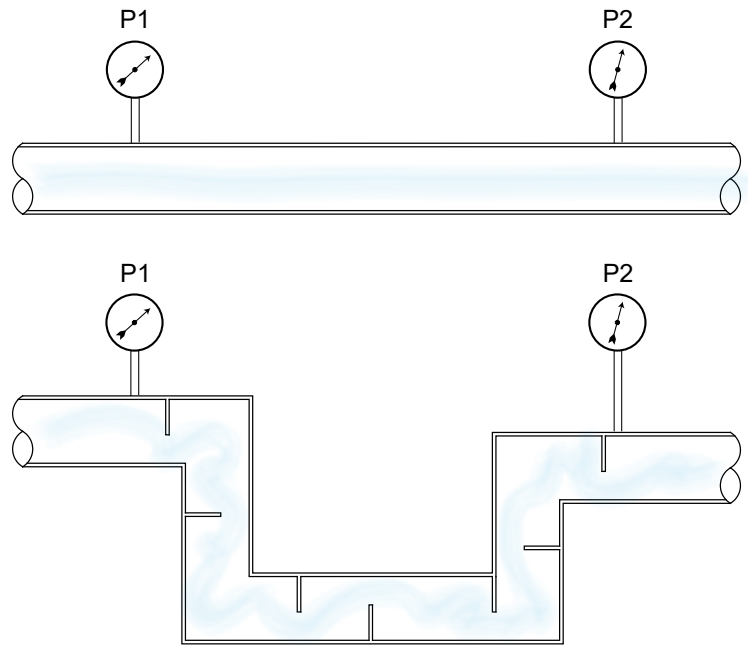


Figure 3. Example of a duct with low flow resistance (top) and with high flow resistance (bottom).

1.2 | Specific Fan Power

The energy performance of a ventilation system can be assessed using the specific fan power (SFP). This is a parameter that quantifies the energy-efficiency of fan air movement systems. It is a measure of the electric power that is needed to drive a fan relative to the amount of air that is circulated through the fan and it is measured in kW/(m³/s). It is not constant for a given fan, but is influenced by several factors. It depends on the efficiency of the fan itself, the imposed ventilation rates, the operating time and the total flow resistance of the system (total

pressure drop).

The SFP is linearly proportional to the system pressure drop; this means that major energy savings can be achieved by reducing the pressure losses in the ventilation network to a minimum. Natural, hybrid and optimised mechanical ventilation systems with low-pressure components are reported to achieve considerably lower SFP values than traditional mechanical systems.

$$P = \frac{\Delta p \cdot q}{\eta}$$

1.3 | How to reduce (or remove) the fan energy

The most logical solution for reducing the fan energy is to remove the fan. This is the idea behind the natural ventilation concepts, which rely only on natural forces such as wind and stack effect (movement of air into and out of buildings resulting from air buoyancy, see chapter 4.1) for introducing and removing air in the building.

Naturally-ventilated buildings make use of only natural forces for introducing and extracting air in the buildings. Wind pressure and stack effect are the main drivers for natural ventilation. The building should be designed considering its interaction with the environment already in conceptual stage. In order to make use of natural forces. For instance, shape and orientation influence the wind pressure on the façade and therefore the natural ventilation potential. Building add-ons can also be used, such as wind catchers and solar chimneys, for increasing the natural ventilation.

While natural ventilation can lead to considerable energy savings by completely removing the fan energy consumption, it also has several

issues. For instance, it offers little to no control on the indoor comfort and air quality, which is not acceptable in several industrial and sport buildings, as well as in hospitals; certain building types (e.g. laboratories, cleanrooms manufacturing halls) require strict pressure hierarchies in order to avoid dispersion of toxic substances. For these and many other reasons, several buildings cannot possibly avoid the presence of fans. It is however a misconception to think that fans are necessarily related to high pressure systems.

Apart from purely mechanical and natural ventilation systems, a whole range of hybrid solutions is possible. For instance, backup fans can support the natural ventilation or mechanical ventilation systems can make use of wind catchers and solar chimneys for saving energy. Other systems make use of mechanical ventilation only during heating and cooling seasons, while during shoulder seasons natural ventilation is used.

When the use of neither natural or hybrid ventilation systems is no viable solution for technical or economical reasons, traditional mechanical systems can be optimized with a careful design and choice of components in order to reduce the overall pressure loss and thus the fan energy.

The best way to reduce the fan energy is to have no fan!

This is the case of **natural ventilation**, which however is not always possible.

A range of hybrid **mechanical + natural ventilation** solutions are available.

Hybrid ventilation systems require a high degree of **architectural integration**.

However, also best practice for mechanical ventilation systems requires an integration with the building architecture for achieving best aesthetical results and lowest energy consumption.

No matter what the final strategy is, ventilation should always be considered since conceptual design, for best results.

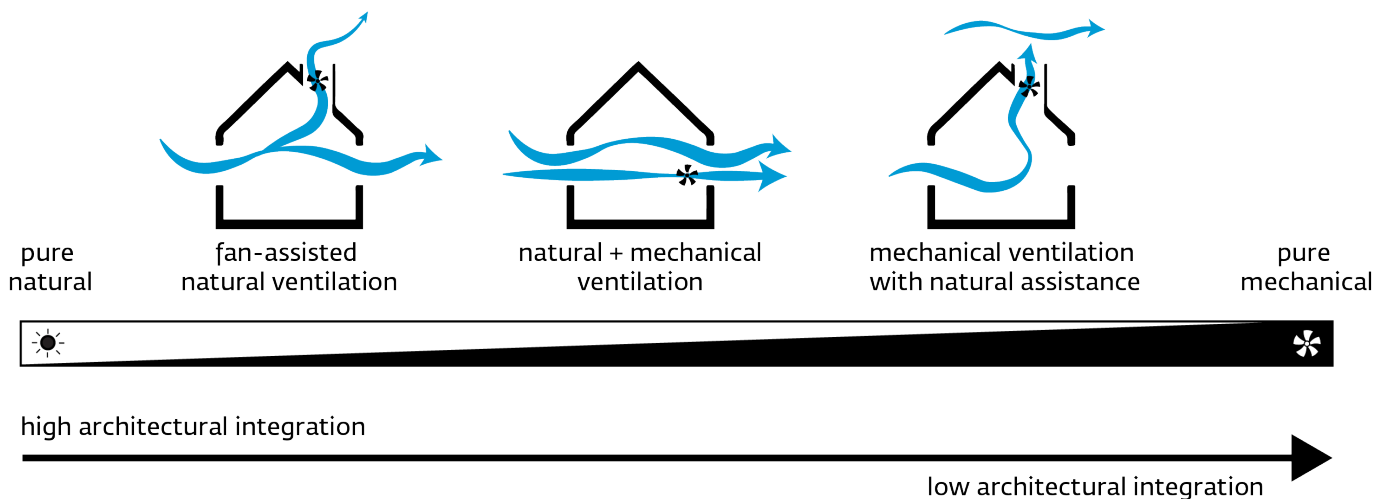


Figure 4. Between the two extremes of purely natural and purely mechanical ventilation there is a large range of hybrid solutions. The more use is done of natural ventilation, the more architectural integration is needed [5].

The following chapters will focus on optimized and advanced mechanical ventilation systems and on the description of different types of hybrid systems, while natural ventilation will not be treated.

As described in the scheme in Figure 5, mechanical ventilation systems can be improved:

- by using advanced control strategy for reducing the airflow and the usage of the system.
- by optimizing each component for reducing its flow resistance, omitting some components (when possible) and/or integrating part of the ventilation system in the building itself;
- by adopting alternative distribution techniques, such as diffuse ceilings, floor plenums or ringed ducting systems.

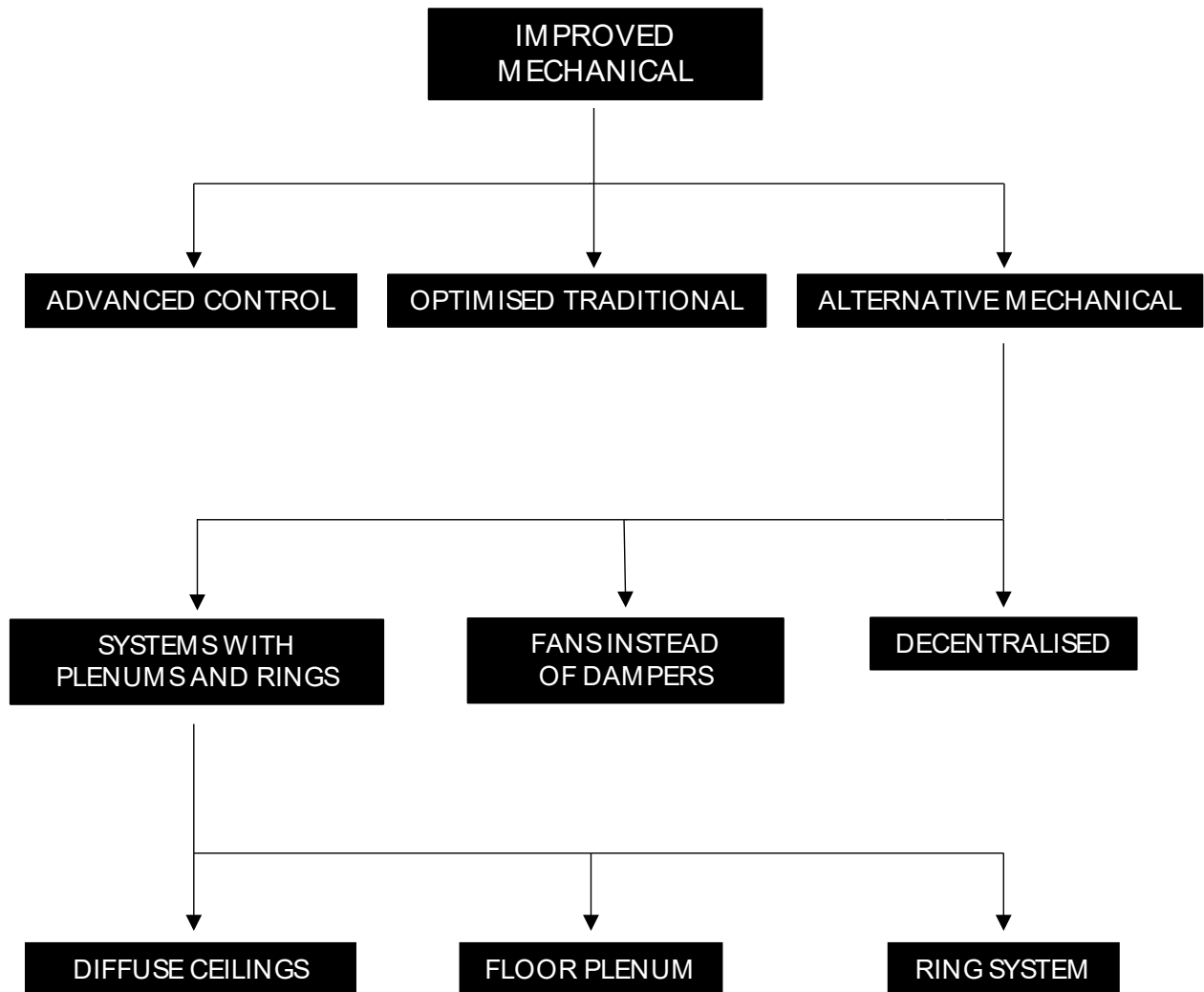
Hybrid systems can be classified depending on their strategy for

mixing natural and mechanical ventilation. In particular, two alternatives are discussed:

- two-mode systems: switching in time between natural ventilation and mechanical ventilation;
- mixed-mode systems: mainly a natural ventilation system but with support of mechanical ventilation (fan assisted) or mainly a mechanical ventilation system, but whereby the available natural forces are optimally used.

Particular attention will be given to the concept of architectural integration. In fact, traditional mechanical systems do not require any special integration in the building, apart from the reservation of space for the ductwork. On the other hand, when importance is given to the reduction of fan energy and alternative or optimized ventilation systems are adopted, a further degree of architectural integration is required.

1.4 | Classification of low-pressure systems



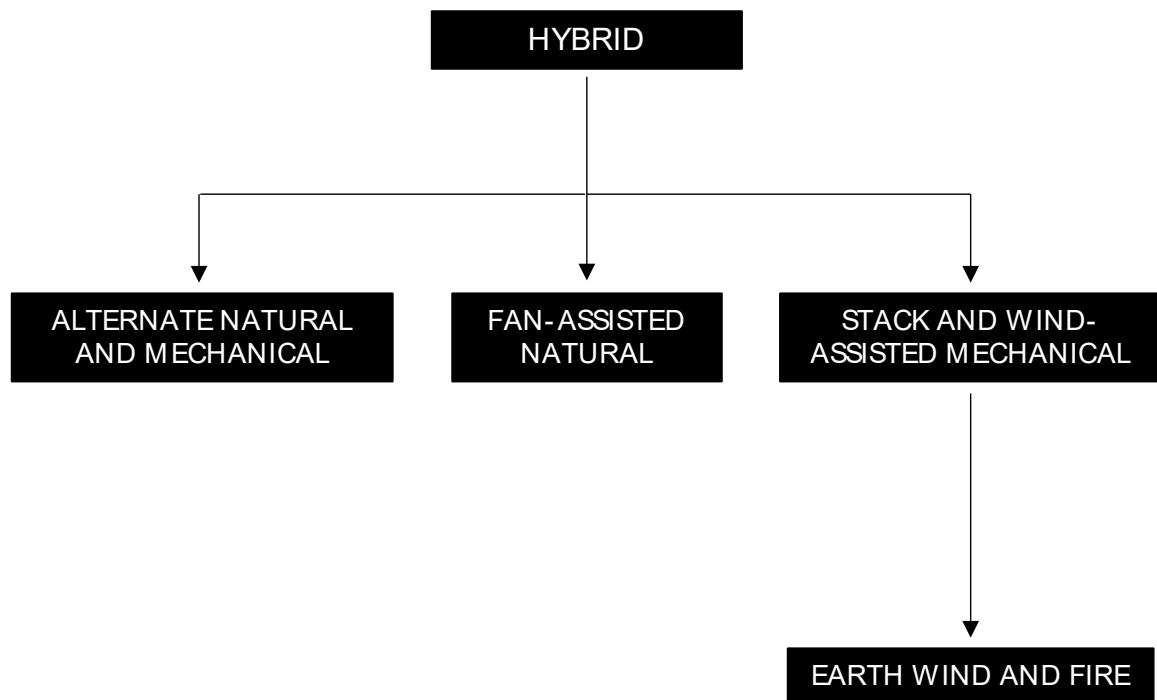
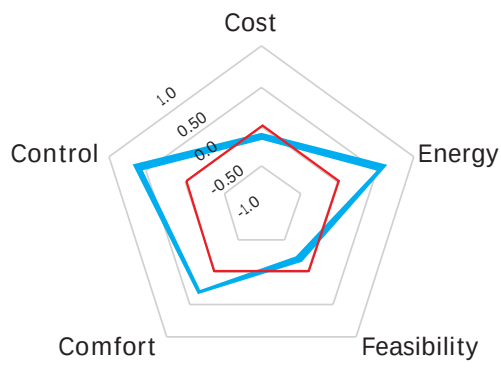
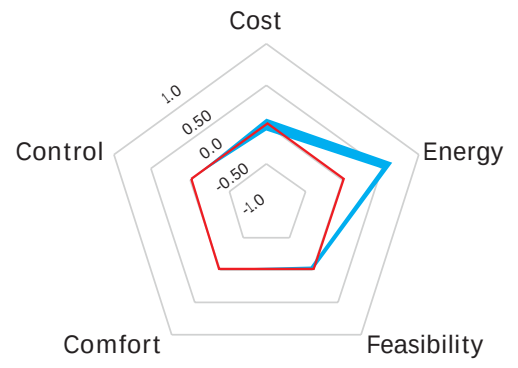


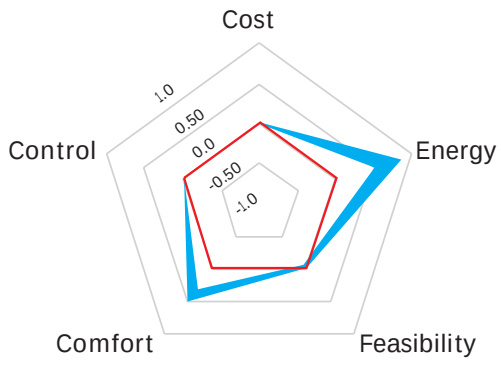
Figure 5. left page: classification of different strategies for reducing the pressure drop in mechanical ventilation systems. Right page: classification of hybrid ventilation systems.



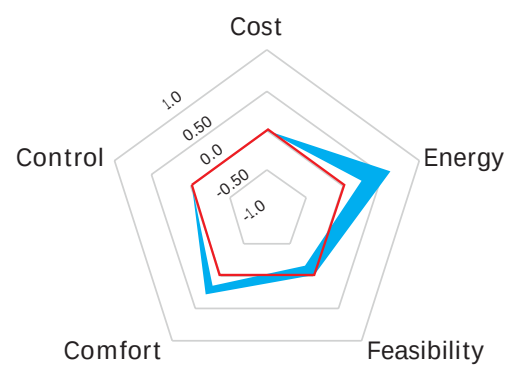
Advanced control



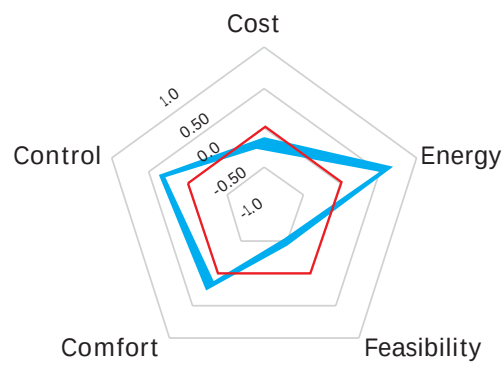
Optimised mechanical



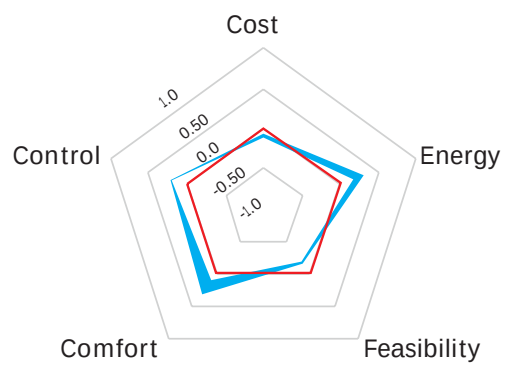
Diffused ceilings



Floor plenums

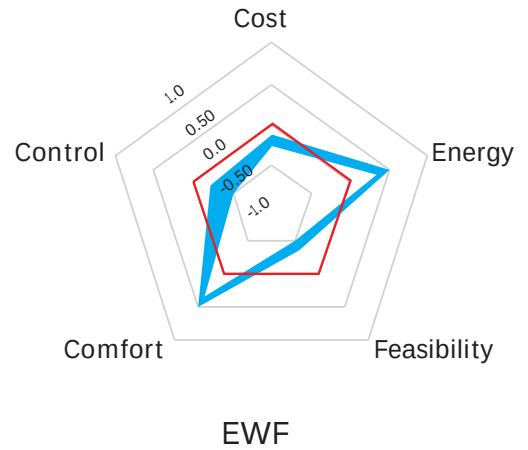
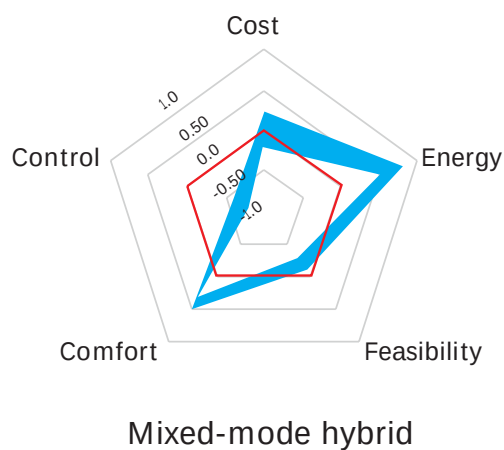
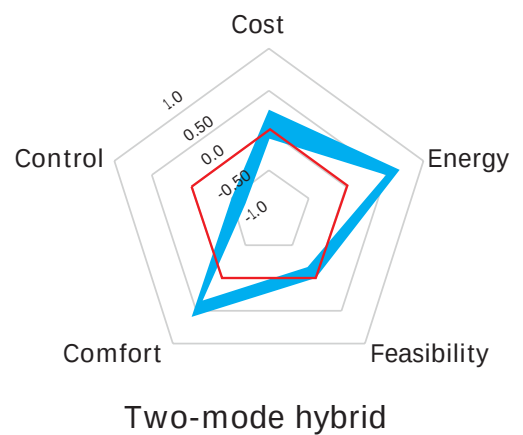
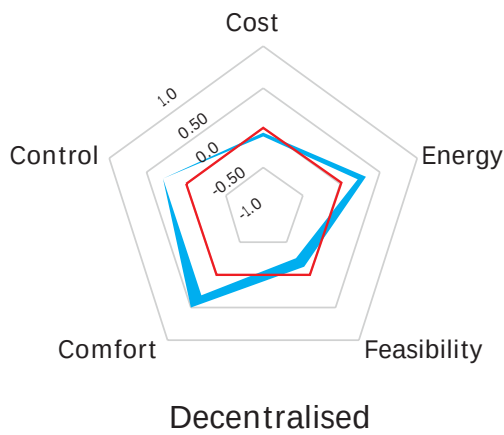


Ring systems



Fans instead of dampers

— Low-pressure system
— Traditional system



The radar graphs in this pages compare the different low-pressure solutions discussed in the booklet with a traditional ventilation system. Five key performance indicators (KPI's) are chosen: Energy (savings), Feasibility, Comfort, Control and Cost. The red lines show the basis KPI's for the traditional systems, all normalised at 0. The blue areas show a range of KPI's for the low-pressure systems, where positive values mean an improvement and negative value a worsening. The graphs should be read in the following way:

- KPI Energy: positive values mean higher energy saving (e.g. 0.5 means that the proposed low-pressure solution can lead to an energy saving of about 50%)

- KPI Cost: positive values mean lower initial investment (e.g. 0.3 mean that the low-pressure system requires an investment which is 30% lower than a traditional system);

- KPI Control, Comfort and Feasibility: positive values mean that the proposed solution offers better control, more control and is technically more feasible than a traditional system.

1.5 | Design philosophy

Traditional mechanical ventilation systems can be installed in any building, in any location in any climate and for any application. Although the integration of the installations at an early stage of design always leads to best results, a mechanical ventilation system can be designed and installed without any early involvement in the building design process. Despite the often suboptimal results that the traditional design process leads to, this is still common practice most likely due to a general reluctance to adopt a different design method, which is perceived as riskier. In fact, designing low-pressure ventilation systems (either mechanical or hybrid) requires a different design philosophy, not just because of the earlier integration, but also because mass produced off-shelf products cannot always be used, while tailored component might be necessary. This results in more time spent on the design compared to the traditional method. This chapter will briefly describe and schematise the design process for low-pressure ventilation systems.

An integrated design process requires architects, civil engineers, indoor climate and energy consultants to be all involved simultaneously. Often, also the interaction with the developers and the building owners is necessary. The design process should be carried out in a logical, sequential manner, within increasing richness of detail as the final design is approached. Figure 6 shows a schematic of the design process starting from the program phase and conceptual design until

the final commissioning of the ventilation system. The procedure is aimed at achieving good indoor comfort conditions with low energy consumption and a tight integration of the HVAC solution with the building design and the local environment. The described procedure is loosely based on the method proposed by [11].

Program phase.

In this phase all general requirements for the building are decided, including goals for indoor comfort, maximum energy consumption, sustainability, etc. It is important to include in this phase not just the developer and the architect, but also the building physics and installation engineers.

Conceptual design phase

In this phase, a series of “quick scans” are performed. It is important to analyse the local climate in relation to the position and orientation of the building in respect to its surroundings. In this way, designers can have a first idea of the possibility to exploit natural forces, such as wind and sun, and of local air quality. A strategy for building energy supply and the HVAC system must be decided. Depending on the possibilities and limitations of the particular building and site, the preferred ventilation system type may turn out to be a traditional mechanical, a low-pressure mechanical or hybrid system. The architect and the engineer should agree on a series of issues, such as:

- Space reservation for installations and ductwork, both

traditional or alternative strategies

- Space reservation for low-pressure solutions, such as diffuse ceilings, underfloor ventilation, decentralized systems, etc.
- Location and space reservation for hybrid ventilation systems, such as solar chimneys, climate cascades, wind catchers, etc.
- Integration strategies, e.g. using atria and stairwell for distributing the air throughout the buildings, culvert and embedded ducts for the air intake and filtration, etc.

Also the developer should agree on such issues, which might lead to a higher initial investment. For this reason, the advantages of using such alternative strategies should be made clear, in particular

- the energy savings during operation should be calculated in order to estimate the payback time and the avoided CO₂ emission
- the improvement of the indoor comfort should be quantified
- possible savings on materials should be calculated
- it should be made clear how the proposed strategy are helping the project to meet the sustainability goals
- all the above-mentioned strategies should be framed not just as expensive add-ons in the short term, but rather as economically and environmentally viable solutions throughout the building life cycle, as well as interesting unique selling points for the project.

Preliminary design

In this phase, the technical design of the ventilation system starts. The building concept develops into specific architectural and technical solutions and systems through sketches, additional calculations and adjustments. This includes the calculation of the heating, cooling and ventilation loads (for the whole building and per room) and a preliminary, simple design of local and general ventilation and space heating/cooling solutions and control strategy. The low-pressure ventilation system layout is designed. The necessary air flow rates as well as expected indoor air quality and temperature levels are calculated. A coarse yearly energy consumption is calculated together with the necessary peak power demands. If the results do not meet the targets, the building and its systems will have to be redesigned before entering the next phase. In this phase the architectural integration of the ventilation system is further refined. It is important that architects and engineers continue collaborating closely; the effect of many architectural design changes on the ventilation system should be assessed within an iterative process.

Definitive design

This is the phase where the building design is made definitive and little changes are considered. The types and locations of the low-pressure ventilation system components are selected as well as the control strategy and the locations of possible sensors. Using hour by-hour calculations for a design year the

whole system (building and technical systems) is optimized with regard to indoor climate, energy use and costs. All issues related to the architectural integration of the ventilation system have already been solved in previous phases. In this phases only minor changes are considered. However, the collaboration between architects and engineers should be maintained.

Design evaluation

In this phase, detailed predictions of indoor air quality and thermal comfort can be performed to check whether the design fulfils the targets of the project.

Commissioning

This is a regular building commissioning phase where it is checked if installed systems deliver according to the design values and if room environments comply with the design targets.

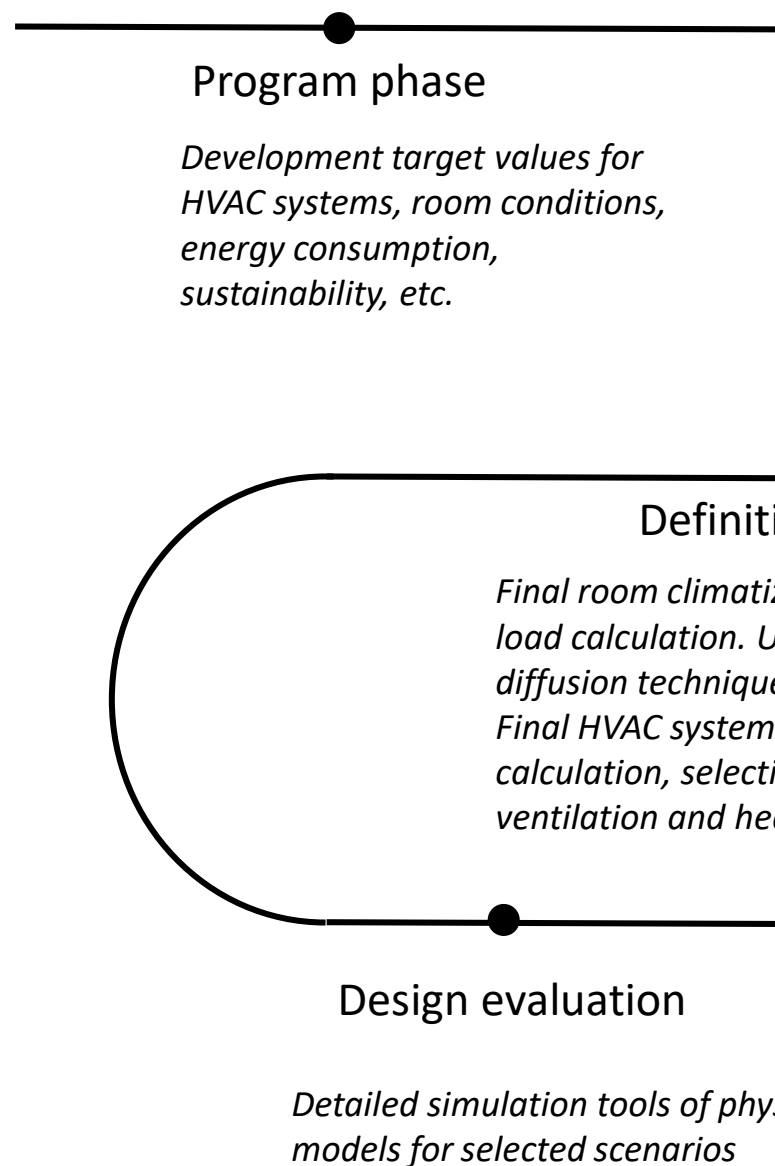
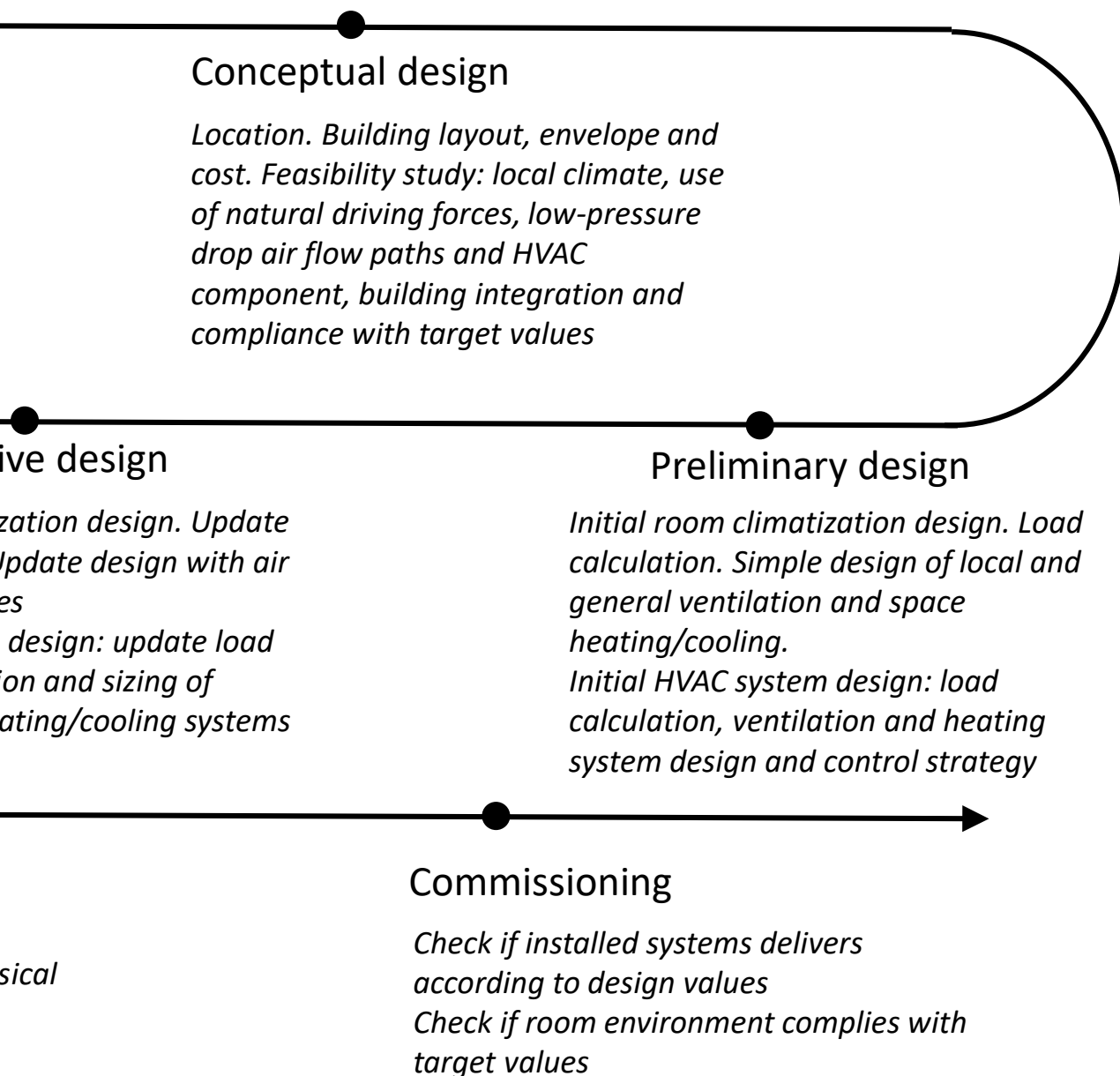


Figure 6. Scheme of the different design phases.



Design example 1 - A large office building with 2 atriums and a diffuse ceiling

Location: Brussels
Architect: CONIX RDBM Architects
Project status: competition
Client: AXA Real Estate



Figure 7. A large office building with 2 atriums and a diffuse ceiling. Courtesy of Conix RDBM Architects.

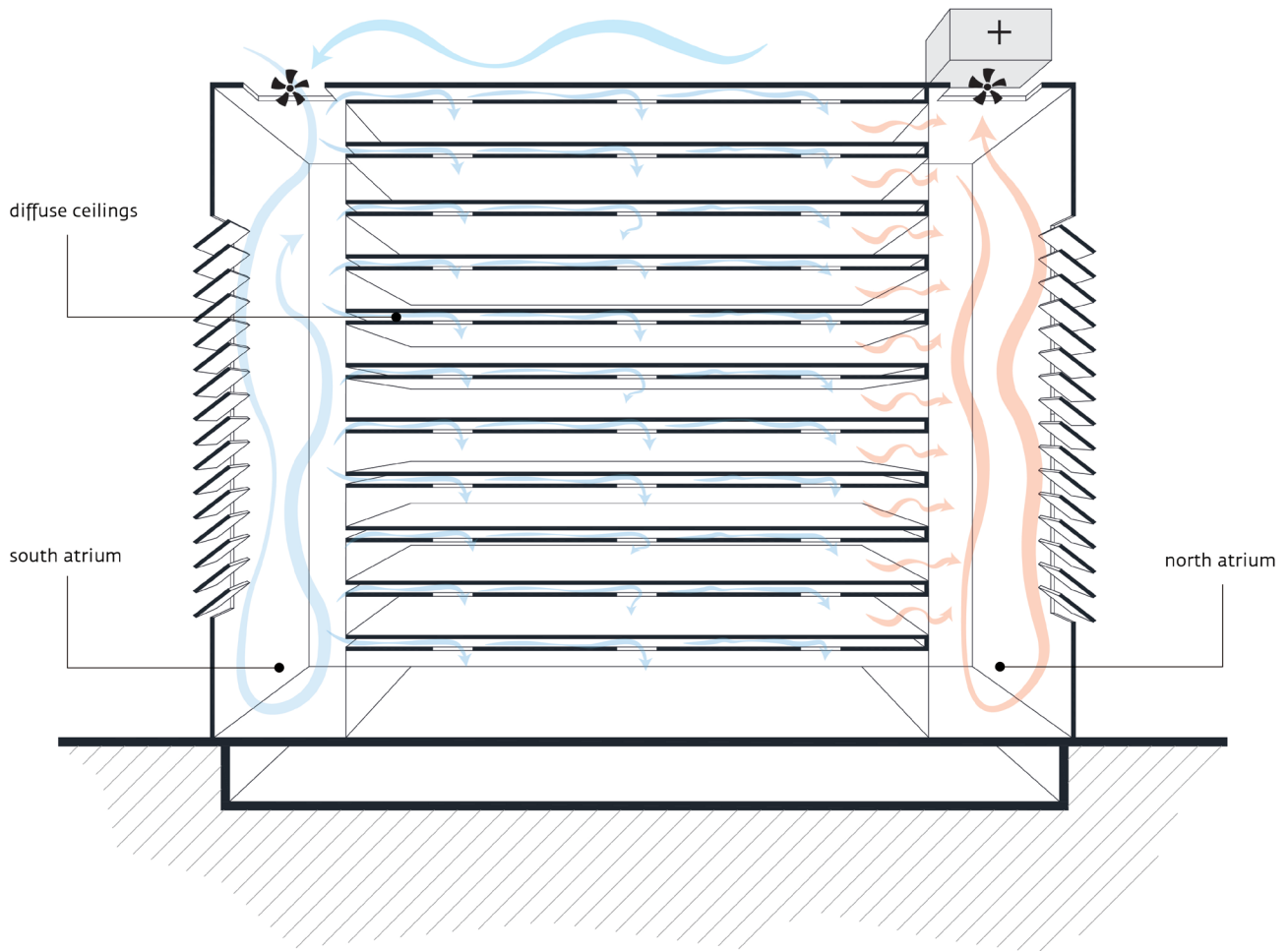


Figure 8. A large office building with 2 atriums and a diffuse ceiling: functional scheme of the air distribution system, where the two atria work as supply and exhaust air shafts.

In a design competition the target was to develop a new Office building of 70.000 m² in the centre of one of the major capitals in Europe. The building had to be energy neutral with a high level of sustainability and circularity. For a number of reasons (light weight, constructability, circularity and sustainability) the building structure was foreseen to be made in CLT wood.

The 10-storey building has an H-shaped floorplan with two large atria, one in the North and one in the South side. The south atrium is used as a space to precondition the air to a certain level and distribute the supply air to the various floors. The north atrium acts

as a collector for the return air. As the building is planned to be constructed in wood, the idea is to use the hollow spaces in the floor package for distributing the air over the floors to the individual office spaces. The supply of air to the rooms is based on a diffuse ceiling principle (see Chapter 3.3.a), assisted with locally placed DC-fans per room, controlled by CO₂ sensors. The air is extracted from the rooms via an overflow damper, released into the central corridors and from there to the exhaust atrium. Figure 8 illustrates the schematic principles of the building set up and the floor construction. The maximum pressure difference for the local fans was calculated to be 30 Pa.

Design example 2 - A laboratory building with a ring ducting system

Location: Leiden
Architect: Inbo + JHK Architecten
Project status: in construction
Client: University of Leiden



Figure 9. Leiden University New Science Campus. Courtesy of JHK Architecten.

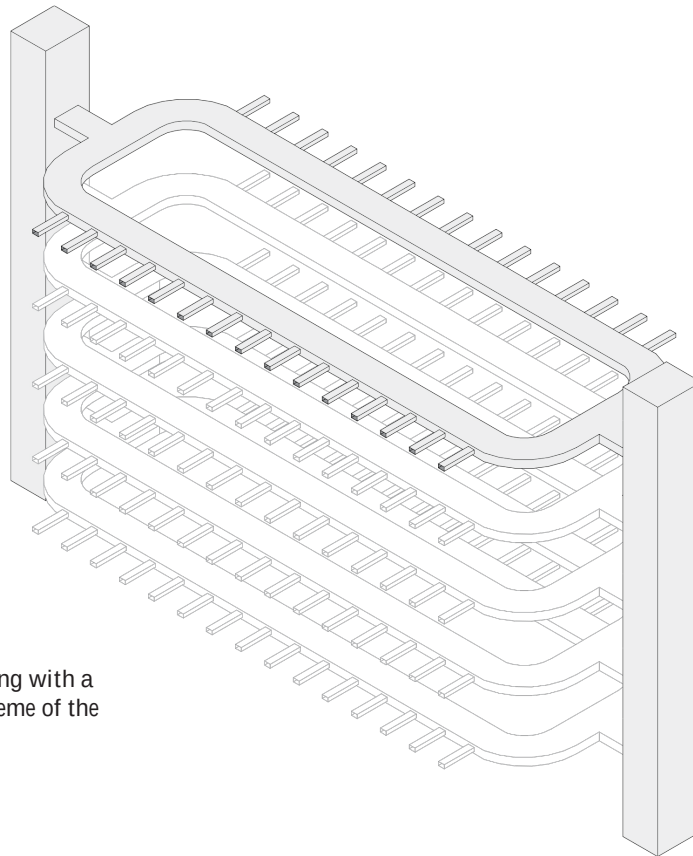


Figure 10. A laboratory building with a ring ducting system. 3-D scheme of the duct network

In laboratory buildings safety always comes first. For chemical laboratories, safety requirements impose large amounts of ventilation air. But also for these type of buildings the present energy related requirements are strict. The question in this case is to design a new educational and research laboratory building of 35.000 m² with a high level of flexibility. The building is the second phase of a 100.000 m² building. In the first phase, a mechanical ventilation system with a conventional, optimised branched ductwork was designed. During its operation, this system showed much higher pressure losses and energy consumption than calculated and the central fan was not able to cope. This led to several necessary adjustments and additional costs. The result was a critical working ventilation installation of 210.000 m³/h with a pressure difference over the fans of 1.800 Pa.

For the second phase of the project, a robust, safe, energy friendly and flexible installation is designed with a low-pressure, ring-shaped ductwork infrastructure.

The concept has several advantages over a traditional branched ductwork:

- The uniformity in size of the ducts and branches makes it easier to produce and install;
- The uniform pressure differences over the system makes it easy to adjust and control;
- The system can be designed as a low-pressure system with less fan energy;
- The system has a high level of flexibility as long as the total air volume for the whole building is not exceeded.

Such a system requires a high degree of integration in the architectural design and for this reason needs to be implemented in the first design phase, as the ductwork is not "as flexible" as usually presumed by the architect.

Design example 3 - Manitoba Hydro Place

Location: Winnipeg (Canada)

Architect: KPMB Architects, Smith Carter Architects, Prairie Architects

Project status: completed in 2009

Client: Manitoba Hydro

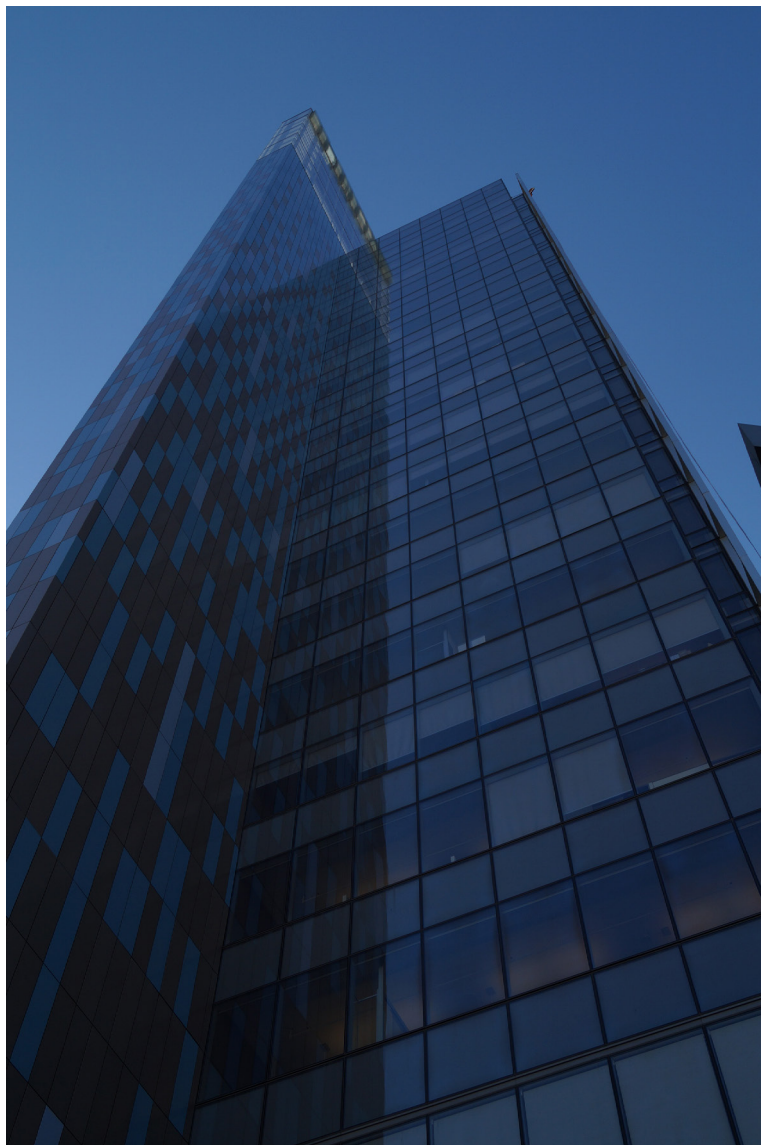


Figure 11. Facade and solar chimney of the Manitoba Hydro Place tower.

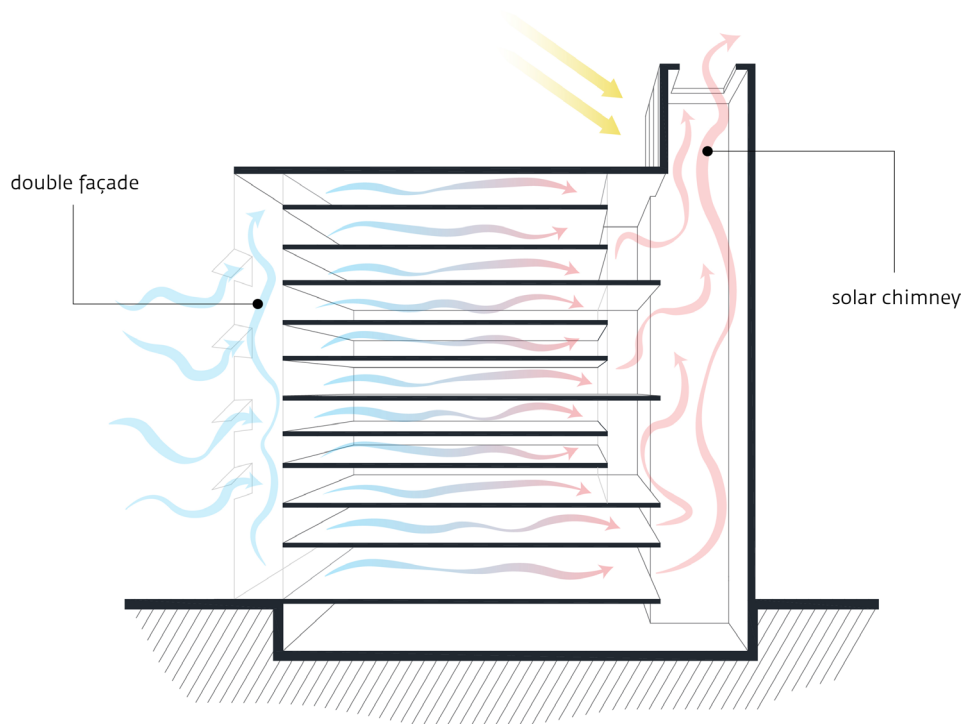


Figure 12. Functional scheme of the air distribution system through the double-skin facade and the solar chimney.

This innovative office building in Winnipeg combines a parking garage, a 3-story podium, containing offices, restaurants and retail, with two narrow 18-story office towers linked by winter gardens. The city, with its winter design temperature of -35°C and a summer design temperature of 30°C , presented the project team with unique climatic challenges. The energy efficiency of the building is maximized in different ways:

- the orientation is optimised in order to use passive solar gains to condition the interior space;
- high ceilings are used to increase natural daylighting
- fresh air is passively pre-conditioned in envelope buffer zones as winter gardens and double facades
- a highly efficient heat recovery reduces energy consumption by pre-heating intake air
- a low-pressure ventilation strategy is in place consisting of operable windows and a solar chimney to allow for hybrid ventilation: the

fresh air flow inside the buildings via openings in the double-skin facade, where it is partly pre-heated and is then collected and exhausted via the solar chimney

The building dynamically adapts to the continuously changing climatic conditions. Occupants can control their individual environment according to their own personal preference using operable windows, lighting and shading devices. The building consumes $140 \text{ kWh/m}^2/\text{year}$ of primary energy for building operation, establishing it as the most energy efficient office tower in North America, 60% below a typical office tower. Beyond energy efficiency the building provides a new level of thermal and visual comfort, with all workstations having access to the façade.

Design example 4 - Debitel Headquarters

Location: Stuttgart (Germany)
Architect: RKW Architektur + Städtebau
Project status: completed in 2004
Client: Step GmbH Stuttgart



Figure 13. Debitel Headquarters tower with solar chimney.

The headquarters of the telecommunications company Debitel comprises a high-rise building and four oblong low-rise buildings that are connected with the high-rise through a glass corridor 100 m (110 yd) long. The entire complex is grouped around a central plaza which forms the centre of the development. Underground car parks as well as a data processing centre are located underneath the complex.

The 16-storey high-rise building is equipped with two staircases and one lift tower located on the outside of the structure. In addition, there is a solar chimney attached to the high-rise building facing the central plaza. Besides its technical functionality it serves as a landmark. Dividing the entire complex into several buildings, breaks apart the massive structure and provides a vertical appearance.

One significant part of the architectural conception was to integrate building services into the design: the solar chimney is a visible indication of this approach. Due to its thermal characteristics the chimney

generates sufficient pull to naturally exhaust the used air from the high-rise building. Fresh air is supplied either centrally or individually through opening elements in the façade. This allows the user to regulate the fresh air supply to his or her own comfort level in spite of the height of the structure.

The façade of this building is an alternating façade. Traditional box window façade sections with interior double glazing and exterior single glazing make up parts of this façade. Venetian blinds located between the glass panes serve as sun protection. The other part of the façade consists of fixed exterior sun protection and an interior ventilation wing. This ensures protection from incident sunlight and eliminates the risk of falling.

Design example 5 - Breeze Hotel

Location: Amsterdam (The Netherlands)

Architect: OZ Architects

Project status: completed in 2019

Client: Amstelius / Dutch Green Company / Borghese Real Estate



Figure 14. The Breeze Hotel in Amsterdam.

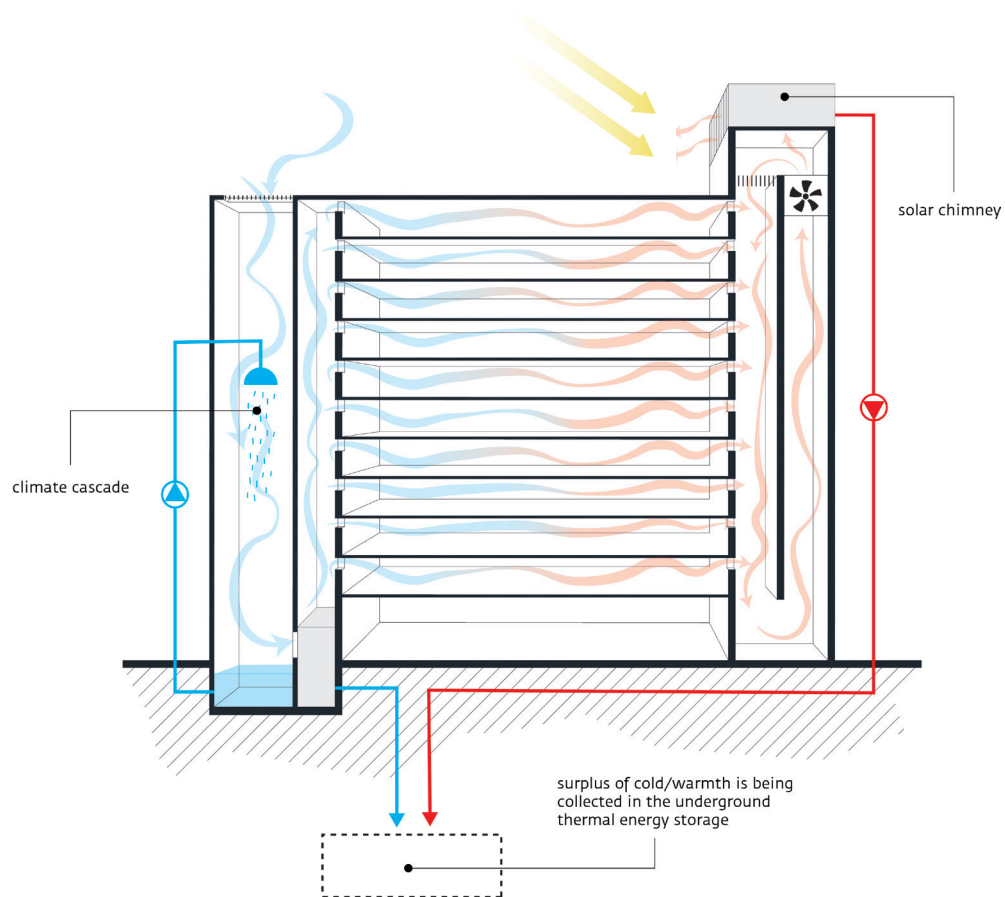


Figure 15. The Breeze Hotel in Amsterdam. Functional scheme of the Earth Wind and Fire system.

The Breeze hotel is the first building to apply the “Earth wind and fire” natural air conditioning concept (see Chapter 4.4) and uses natural processes to ventilate the near 200 rooms of the hotel. EWF applies the use sunlight, wind, and falling water to ventilate and cool down the rooms, and to supply warm water. It is a hybrid ventilation concept, with integrated heating and cooling and assistance of mechanical fans when natural forces are not sufficient. The system is composed by the following parts:

- the climate cascade, vertical shaft within the building that functions as a natural heat exchanger, into which ventilation air with the help of water nozzles is cooled, heated, humidified and cleaned;

- two solar chimneys (see Chapter 4.1), constructed out of glass and

- with a backside of black solar panels, harvest the necessary warmth to move the air upwards;

- the heat exchanger that reuses extracted warmth for heating tap water through an air heat pump and storage under the hotel of residual heat;

- the thermal energy storage system that provides additional heating or cooling as required;

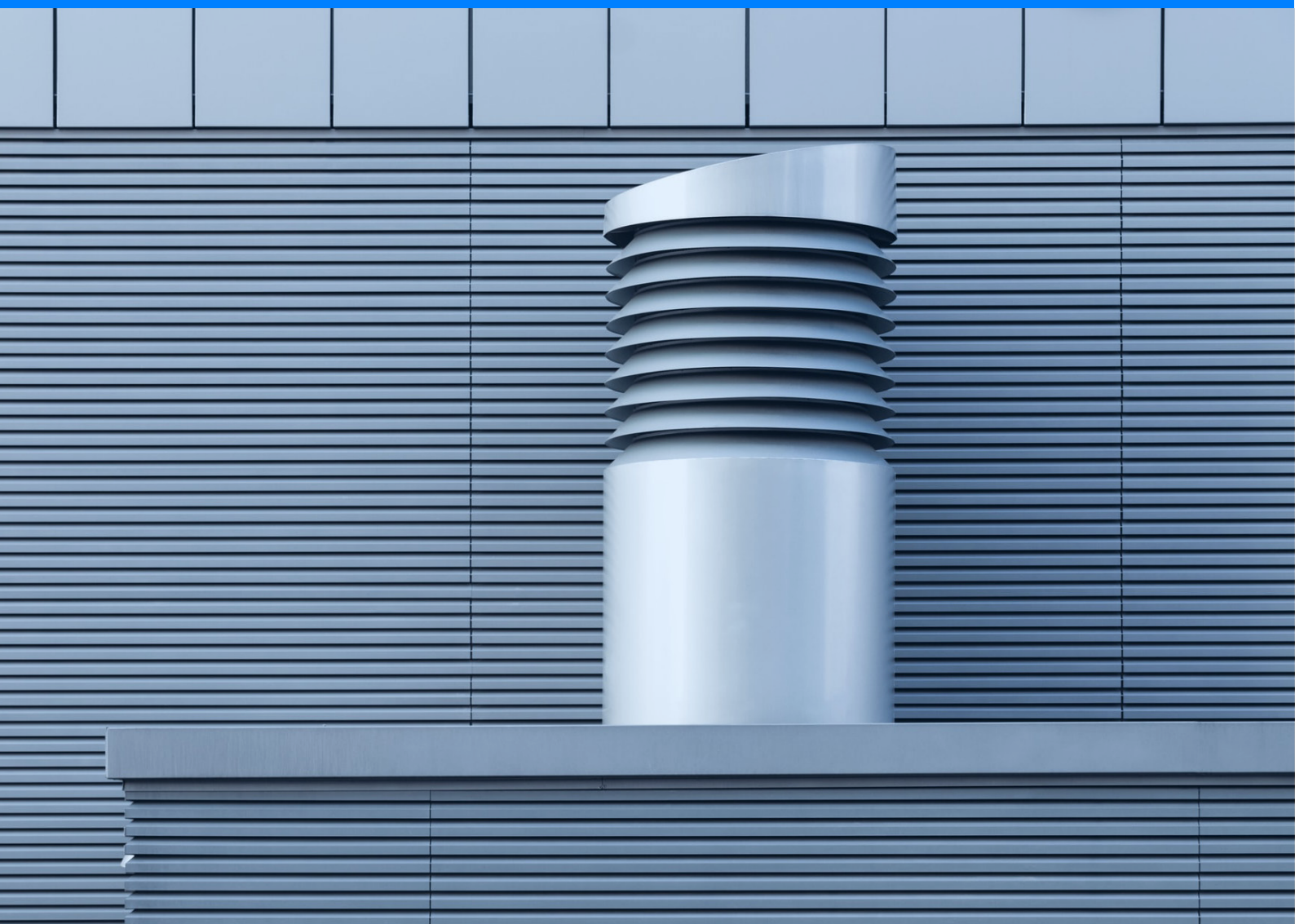
- the solar powered roof and facade with customised building-integrated PV panels and solar panels in the solar chimney and on the awning;

- the sunroof with solar panels.

Components of a mechanical
ventilation system

02

Each component,
each bend in the air handling unit
and each ductwork
increases the **flow resistance**
and in turn causes
higher energy consumption. The solution
is the use of low-pressure strategies
with a high degree of architectural
integration



02 | Components of a mechanical ventilation system

This chapter provides a brief description of the components of a traditional mechanical ventilation system. Each component contributes to a different extent to the total flow resistance of the system. Removing or improving the performance of some components can therefore have larger effects on the overall performance of the system. While some components can indeed be omitted or improved considerably by making use of smart alternatives, certain components cannot be omitted or give very little options for improvement. This chapter will provide an initial description of all components, their effect in terms of flow resistance and their improvement potential. For each component it will be pointed out the possibility of its integration in the building fabric. More technical details are provided in Appendix A and B. Figure 15 schematises this information in a diagram with indicators for flow resistance, improvement potential and effect of integration for each component.

A conventional and complete mechanical ventilation system can be subdivided into two major parts:

- 1) a supply branch, where fresh air is treated and distributed to the spaces;
- 2) a return branch, where air is removed from the space and released in the atmosphere.

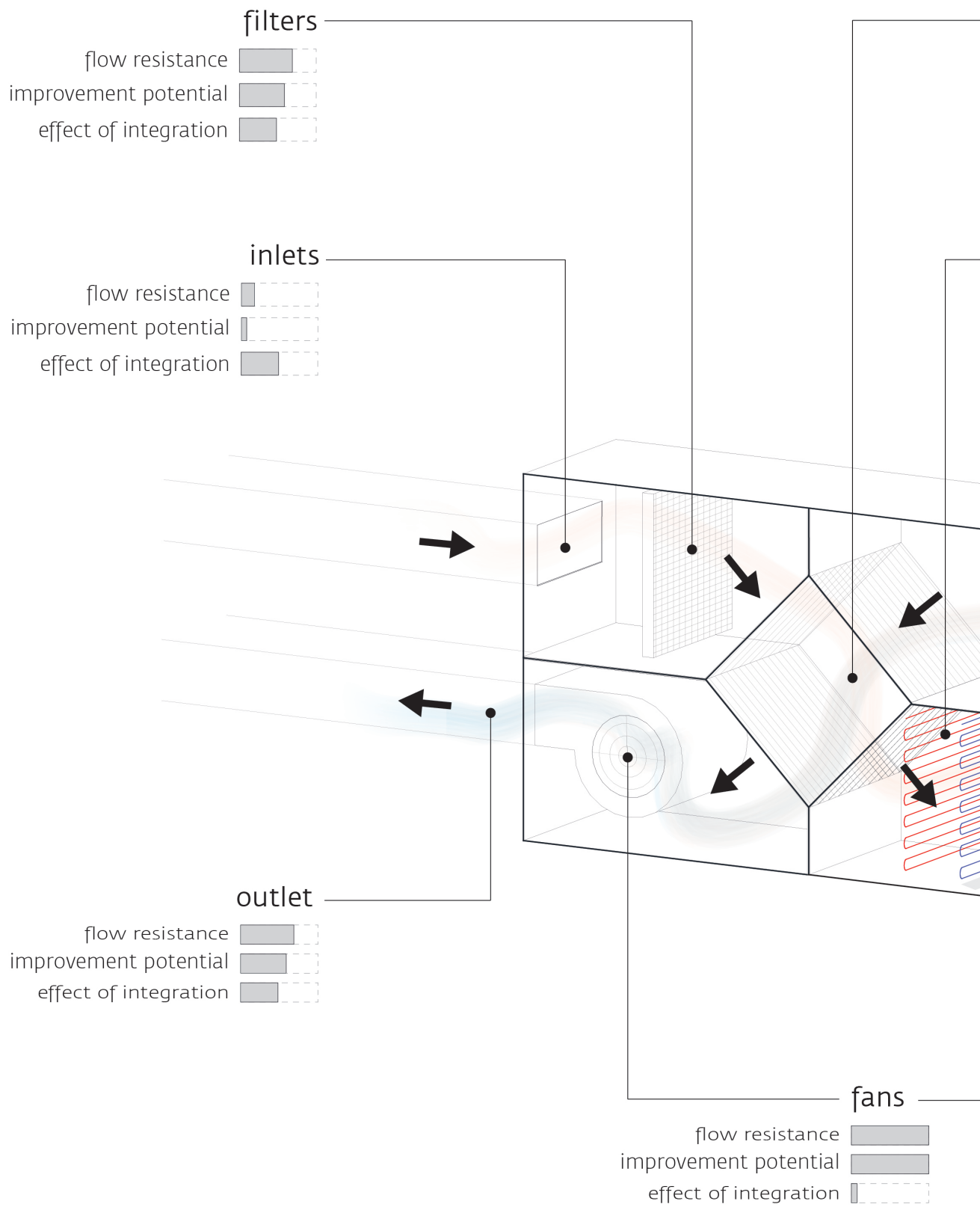
Both branches are composed by two sections:

- 1) the air handling unit (AHU);
- 2) the distribution system.

The AHU is usually a large metal box containing a fan, for the supply air, a fan for the return air, heating and cooling elements, filter racks or chambers, sound attenuators, dampers and a heat recovery system to transfer heat from the return air to the supply air. Not all these elements are always present. The AHU connects to a ductwork ventilation system that distributes the conditioned air through the building and returns it to the AHU. In this chapter, the most important components of an AHU and a distributions system will be described, as well as their effect on the total flow resistance.

Filters

Air filtration is almost always present in ventilation systems. Filters have two main functions: cleaning the supply air from dust and particles and protecting the AHU components from soiling (especially the heat exchanger and the fan). Filtration is therefore typically placed first in the AHU. Most commonly used air filters are bag filters (composed by glass fibre or plastic material) which have a very high flow resistance. A viable alternative with much lower flow resistance are electrostatic precipitators. Integration of filtration strategies with the building fabric is not straightforward, but few examples are available of underground corridors and ducts with electrostatic filters (see also chapter 4.3).



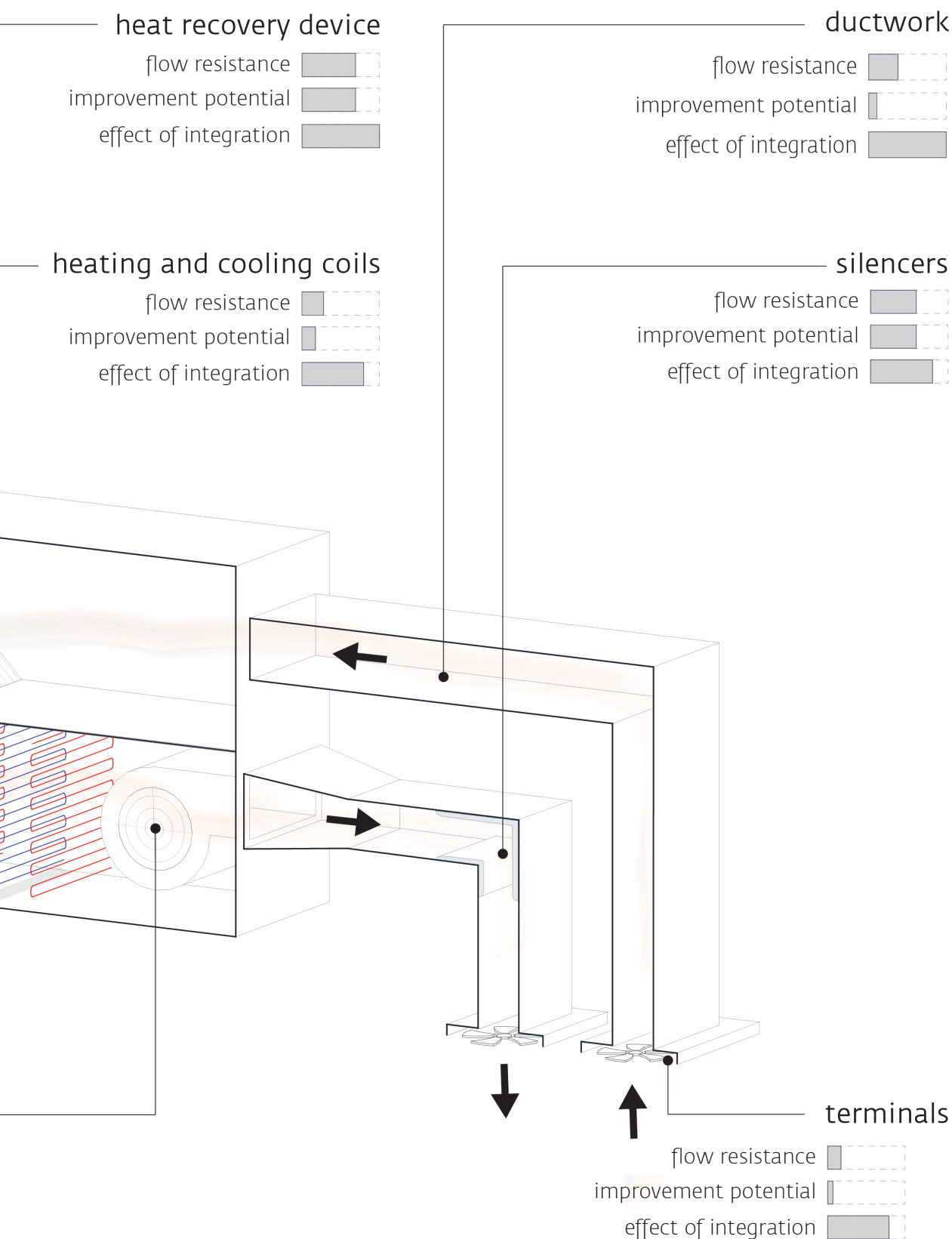


Figure 16. Scheme of an air handling unit with its components. For each component, 2 indexes are shown: the relative contribution to the total flow resistance, the potential of the component to be improved and its specific potential to improve when integrated in the building design.



Figure 17. Different degrees of architectural integration of the ventilation system.



Heating and cooling elements

AHU's may need to provide heating, cooling, or both to change the supply air temperature, and humidity level depending on the location and the application. Such conditioning is provided by heating and cooling coils within the AHU air stream. The most common are coils constituted by copper tubes where hot or chilled water flows and copper or aluminum fins to aid heat transfer. Due to this high concentration of pipes and fins, the heating and cooling coils constitute (together with the heat recovery device, see later) one of the largest flow resistance in the system. The dimension of the coil can be reduced by designing the spaces for low heating and cooling loads or by using ventilation strategies that allow for temperatures of the supply air close to the outdoor temperature.

Heat recovery device

A heat recovery device is a heat exchanger fitted to the air handler between supply and extract airstreams. This allows to "recycle" part of the heat of the exhaust air by transferring it to the supply air. In order to do this as efficiently as possible, a large contact surface between the two airflows must be guaranteed: the air is forced through a myriad of small passages, leading to a large pressure drop. Together with the heating and cooling coils, the heat recovery device is one of the largest flow resistance in the system. Certain ventilation strategies, however, avoid the need for such device (e.g. diffuse ceilings described in Chapter 3.3.a).

Silencers

The fan in the air handler generates noise, which should be attenuated

before ductwork enters a noise-sensitive room. To achieve meaningful noise reduction in a relatively short length, a sound attenuator (or silencer) is used. Due to their volume, silencer can offer considerable flow resistance; however, few aerodynamic options are available in the market (see appendix A and B).

Outlets

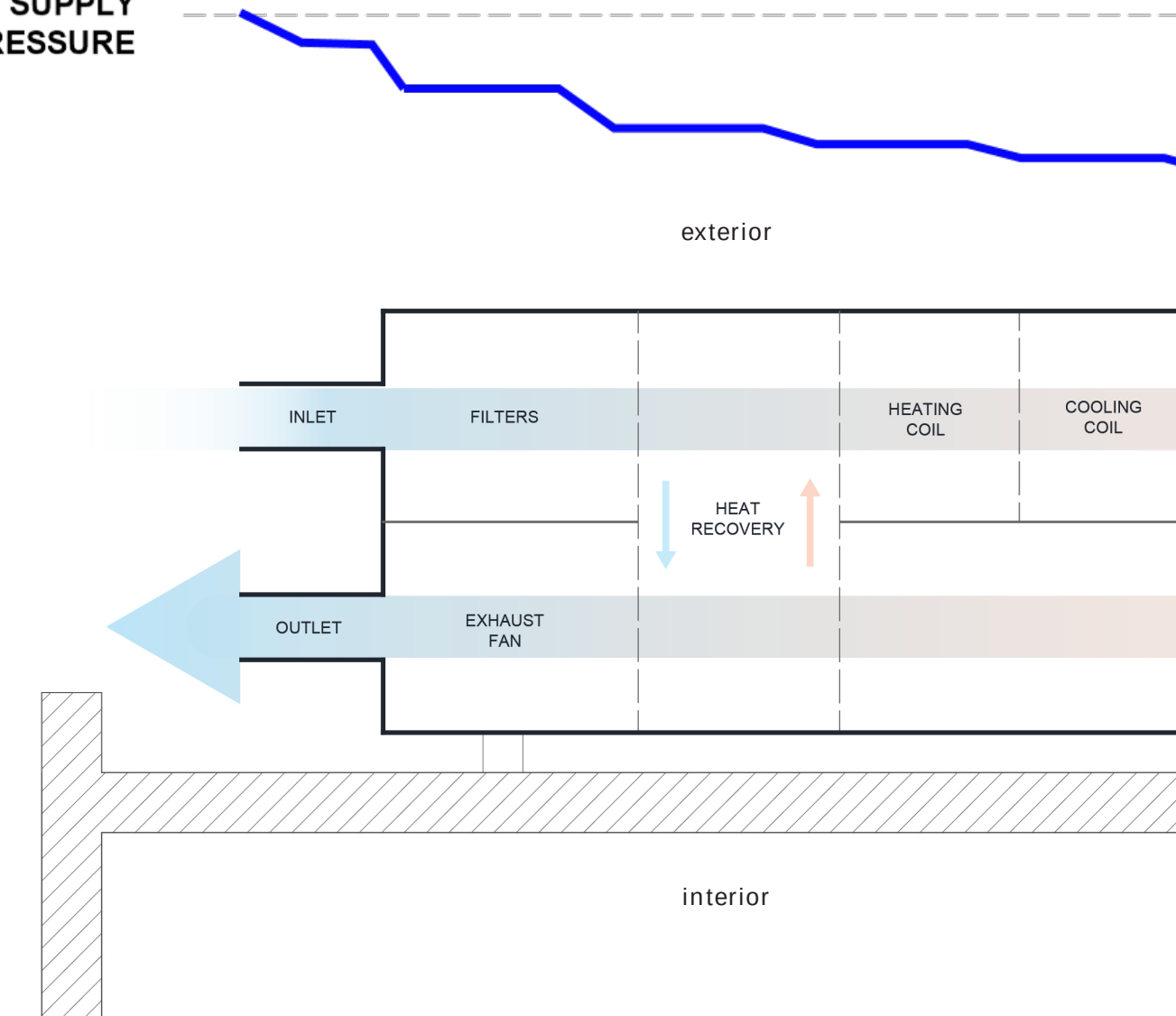
The outlets are the terminal sections of the exhaust duct system, responsible to discharge the exhaust air into the environment, while preventing short-circuiting effect, namely direct recirculation of stale and contaminated air into the supply system.

One option to ensure the best performances is to locate the outlets as far as away from the inlets as possible, but often this is not done either because of a lack of space, either because of poor design strategies. More recommendations are provided in Appendix B on how to place inlet and outlets correctly.

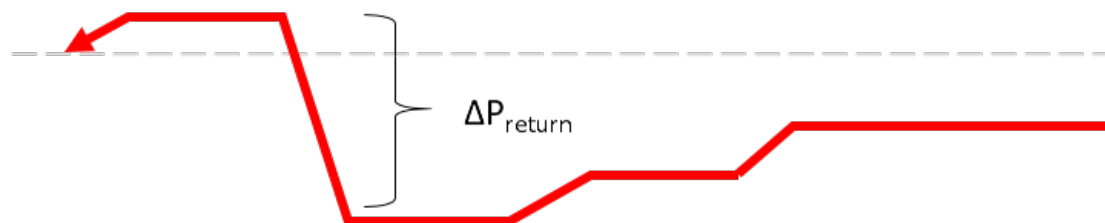
Ductwork

In traditional mechanical ventilation systems, the supply and exhaust air (or just one of the two) moves from the AHU to the space and vice versa via a system of ducts. Most of the times, the duct system consists of a main branch, or shaft, and a series of lateral ramifications that supply and collect air uniformly through the ventilated spaces. The ductwork system has a considerable impact on the overall performance of the ventilation system and its energy consumption. Poor design can cause high pressure losses for each supply and exhaust side [21, 1, 14]. Integration of the ductwork in the building design can lead to great results not just in terms of

**SUPPLY
AIR PRESSURE**



**RETURN
AIR PRESSURE**



The fan needs to overcome the flow resistance of each component in the ventilation system by increase the pressure. The higher the needed pressure, the more energy is consumed by the fan.

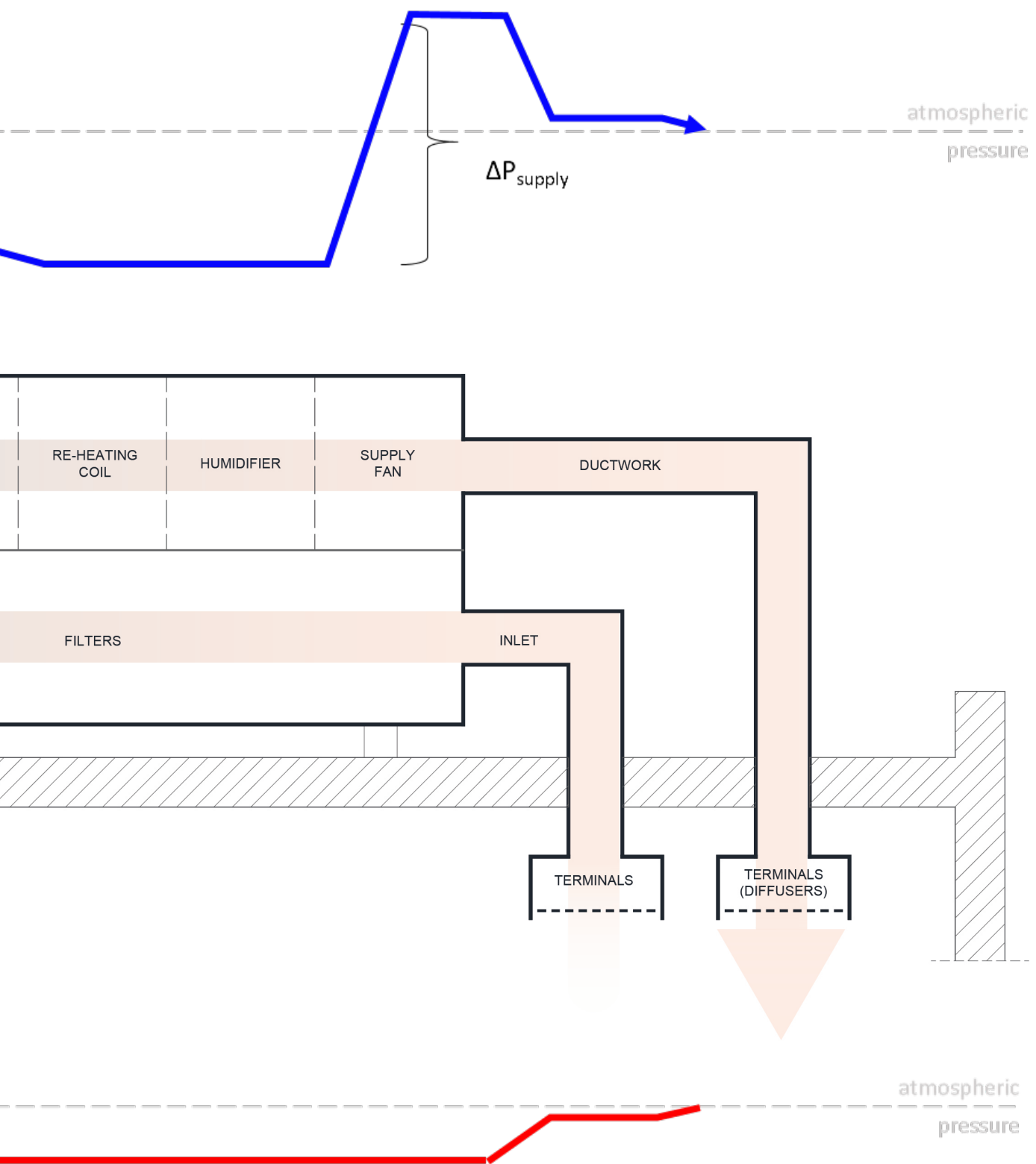


Figure 18. Evolution of pressure inside a conventional mechanical ventilation system. Top: supply side. Bottom: return side. The pressure drop caused by each component is shown, as well as the pressure rise caused by the fan.

In a conventional mechanical ventilation system, the flow resistance can be reduced when a good design practice for all components is followed.

This booklet contains several recommendations on how to achieve this.
(see Appendix A and B)

aesthetics, but can also allow for a simpler network, with larger ducts and less bends and elbows, leading to easier construction, maintenance, material use and, of course, lower flow resistance. However, differently from other components, the flow resistance of the ductwork can be reduced only to a certain extent; in fact, the duct network will always be among the largest source of flow resistance. More details on the design of the ductwork are provided in Appendix B.

Terminals

Air terminal devices are grilles or diffusers at the end of the duct system, which distribute and mix supply air into the ventilated spaces. Their design the air speed strongly affects their pressure drop.

Fan

The components which are listed above are the main sources of flow resistance in the ventilations system, which altogether produce a pressure drop depending on the flow rate. The fan(s) needs to overcome such pressure drop, consuming energy in order to allow the air to continuously flow through the AHU and the ductwork. Counterintuitively, the fan itself can be responsible for a large part of the total flow resistance of the ventilation system. In fact, when the fan is not properly dimensioned or is wrongly placed into the AHU, turbulence and swirls can be generated right at the entrance and exit of the fan. For this reason it is of paramount importance to choose the right fan and design its casing as aerodynamic as possible. Several recommendations are provided in Appendix B.

Low-pressure strategies for
mechanical ventilation

03

A traditional mechanical ventilation system can be designed as a low-pressure system, leading to large **energy savings**!

An efficient strategy for reducing the fan energy is to reduce the air flow through the ventilation system. This can be obtained by using **smart control** systems.

Each component of the system can be optimized for reducing the **flow resistance**. In several situation, some components can be directly removed because not needed.

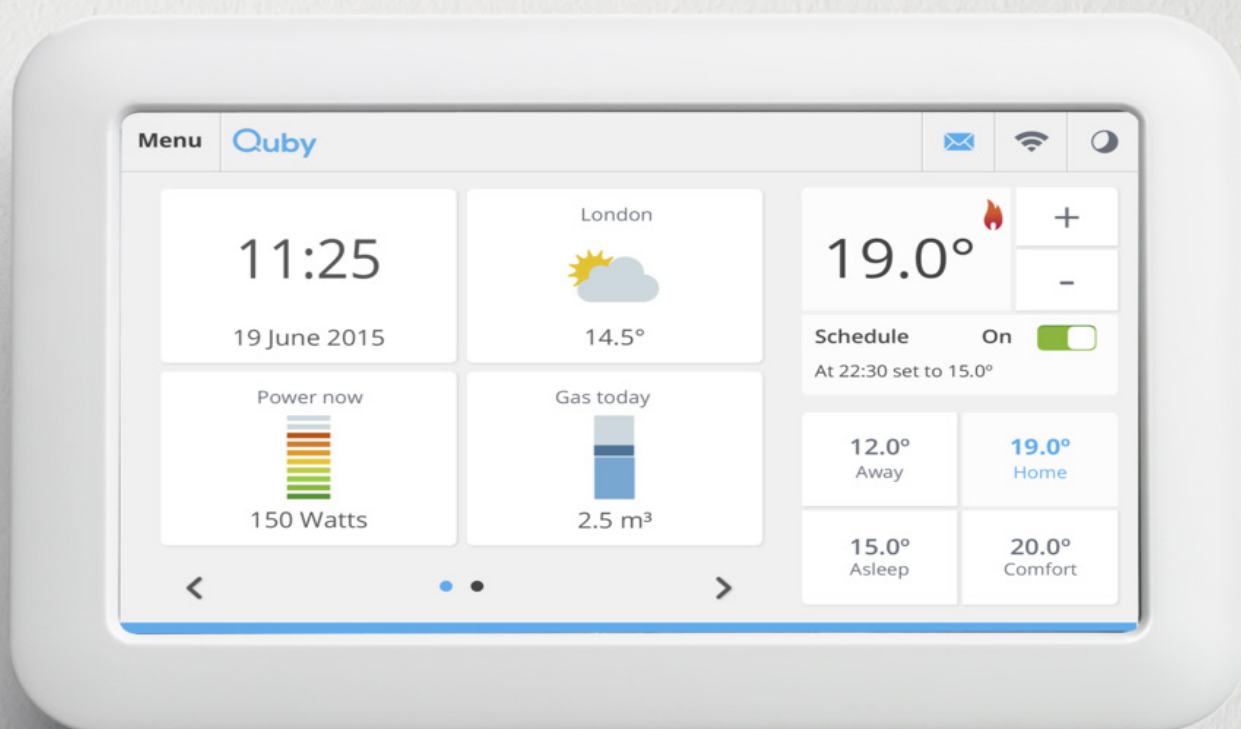
There are also alternative ways of designing an air distribution system, such as climate ceilings, decentralized ventilation, ring systems, etc.

3 | Low-pressure strategies for mechanical ventilation

A traditional mechanical ventilation system can be designed as a low-pressure system, leading to large energy savings. This can be done in different ways, from simpler to more complex.

In this chapter, different strategies for designing low-pressure mechanical ventilation systems will be described. Advantages and disadvantages of the following systems will be presented:

- Advanced control systems;
- Optimised mechanical ventilation systems (this topic will be mainly treated in Appendix B);
- Alternative mechanical ventilation systems such as:
 - Diffuse ceilings;
 - Underfloor ventilation;
 - Ring systems;
 - Fans instead of dampers;
 - Decentralised ventilation.



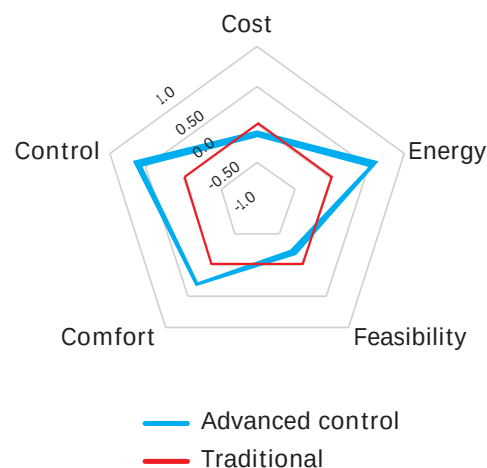
3.1 | Advanced control systems

An efficient strategy for reducing the fan energy is to reduce the air flow through the ventilation system. This can be obtained by using smart control systems.

Demand controlled ventilation (DCV) is a feedback control method that maintains indoor air quality by automatically adjusting the ventilation rate provided to a space in response to changes in conditions such as occupant number or indoor pollutant concentration. Although technically cannot be considered as a low-pressure ventilation strategy, DCV is mainly intended to reduce the energy use for ventilation, as well for heating and cooling, compared to buildings that use open-loop controls with constant ventilation rates.

There are several ways for estimating the occupancy of space, for instance:

- timed schedules;
- motion sensors;
- CO₂ and CO detection;
- Ticket sales
- people counting video software;
- inference from other system



sensors/equipment, like smart meters;

Carbon dioxide and monoxide sensors monitor pollutant levels in a space by strategic placement.

The placement of the sensors should be able to provide an accurate representation of the space, usually placed in a return duct or on the wall. As the sensor reads the increasing amount of carbon dioxide levels in a space, the ventilation increases to dilute the levels. When the space is unoccupied, the sensor reads normal levels, and continues to supply the unoccupied rate for airflow. Using such sensors for DCV was found to reduce energy consumption by 62% when compared with a constant air volume (CAV) ventilation system [29].

Each component of a mechanical ventilation system should be optimized for reducing the flow resistance.

In several situations, some components can even be removed.

Appendix B shows many alternative solutions for each component of the ventilation system, including options for integration in the building design.

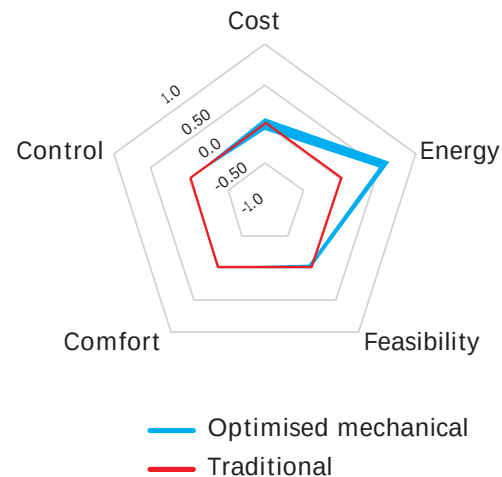
3.2 | Optimised mechanical ventilation systems and design integration

Traditional mechanical ventilation systems can be optimized with a careful design and choice of components in order to reduce the overall pressure loss and thus the fan energy. The graph in Figure A1 shows that with an optimized design, the pressure drop of each component can be reduced up to 80% and, for certain components, up to 100%.

In Appendix B, the following components will be treated:

- Filters
- Heat exchangers
- Intake and exhaust ducts
- Ductwork
- Silencers
- Grilles and diffusers
- Fan inlet and outlet aerodynamic inefficiencies

For each component, recommendations will be given on how to improve its design. When



possible, suggestions on alternative, more efficient solutions will be provided, including possibilities to integrate the component in the building design.

3.3 | Alternative mechanical ventilation systems

So far, only traditional mechanical ventilation systems have been treated and advanced control solutions and component optimization strategies have been proposed.

This chapter will describe some alternative strategies for distributing and exhausting air in a building that can contribute to reducing the total pressure loss and fan energy. The

following distribution strategies will be treated:

- Diffuse ceilings
- Underfloor ventilation
- Use of fans instead of dampers
- Decentralised ventilation systems

Diffuse ceilings can reduce flow resistance considerably by reducing the **air speed** and avoiding the use of a heat exchanger.

3.3.a| Diffuse ceilings

In diffuse ceiling ventilation, an open space between the suspended ceiling and the floor slab functions as an air plenum.

The pressure difference between such plenum and the occupied zone let the conditioned air penetrate through the suspended ceiling, which can be considered as a very large air diffuser through which the air is delivered to the conditioned space at a very low speed and random direction. In this way, the risk of draught is minimized, even when outdoor air at extremely low temperature is directly supplied to the space (down to -6°C).

The air distribution relies on the presence of heat sources in the room (e.g. people, lighting, electrical

equipment, etc.), that generate a buoyancy force, whose strength determines how well the air is mixed in the room: the downward supply flow and the uprising buoyancy flow interact and generate air recirculation in the room.

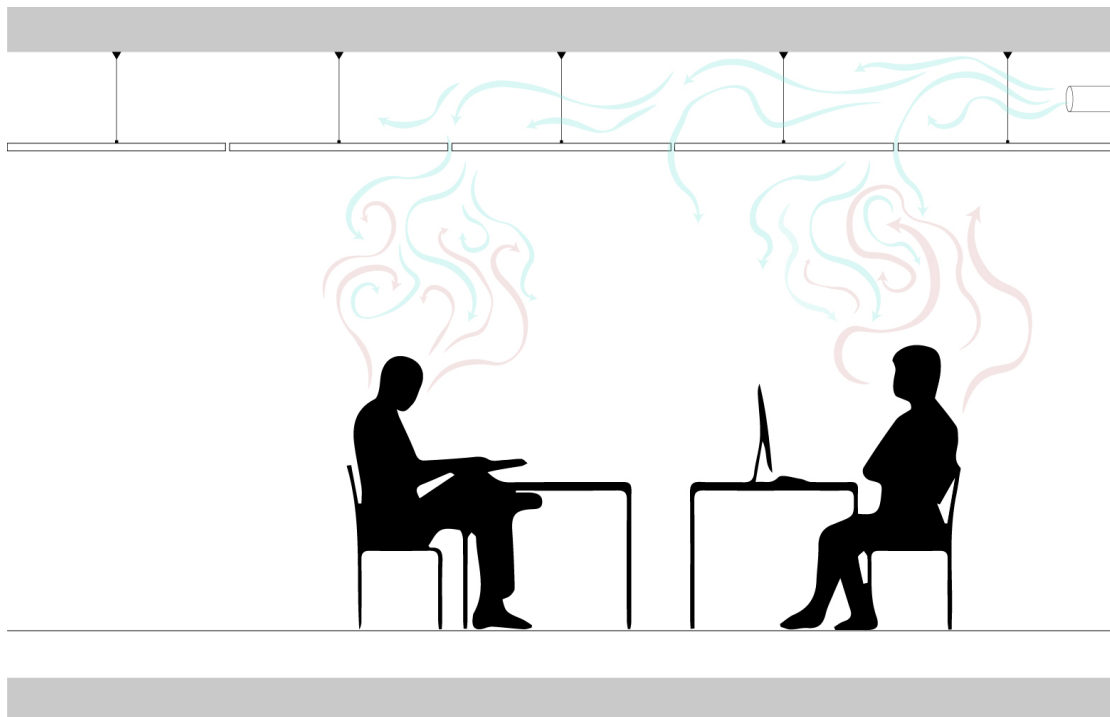
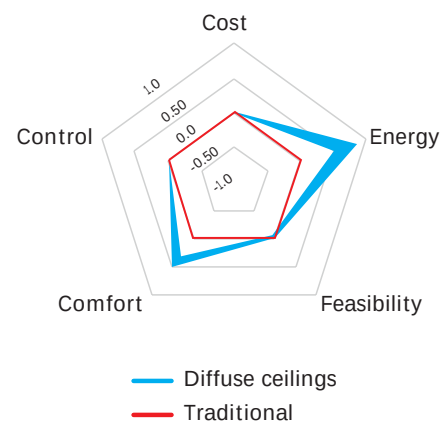


Figure 19. Scheme of a diffuse ceiling air distribution system. The conditioned air penetrates through the suspended ceiling at a very low speed.

Underfloor ventilation systems offer similar advantages as diffuse ceilings in terms of reduced pressure drops in the plenums, but they can lead to slightly worse thermal comfort.

Compared to traditional ventilation systems, diffused ceilings offer several benefits, including considerable energy-saving opportunities.

As far as pressure loss is concerned, the main two benefits are the following:

- the heat recovery and pre-heating systems can be removed. In fact, given the low risk of draught, fresh air can be supplied at low temperature.

This aspect alone constitutes a considerable reduction of the pressure loss in both the supply and return branch.

- the very low air velocity through the suspended ceiling and inside the plenum constitutes an additional reduction of the pressure loss

compared to traditional ducted systems with diffusers, where air velocities are higher and areas smaller.

Additional benefit not related to the pressure loss reduction are the following:

- high thermal comfort, due to the absence of draught and a more uniform distribution;
- thermal energy savings due to the potential absence of the pre-heating unit;
- high cooling capacity;
- low noise level, due to the low air velocity;
- low investment costs and easy installation compared to traditional ducted systems.

3.3.b| Underfloor ventilation

Underfloor ventilation systems offer similar advantages as diffuse ceilings in terms of reduced pressure drops in the plenums. However, air is supplied to the occupied space through regular grills, which offer a higher flow resistance than suspended ceilings. Also, in order to avoid thermal comfort issues with cold air being supplied at floor level (the so-called “cold floor” effect) air must be supplied at much higher temperature than in diffuse ceilings systems.

For this reason, pre-heating and heat recovery are necessary in underfloor

ventilation systems and the achieved pressure loss reduction is lower than for diffuse ceilings.

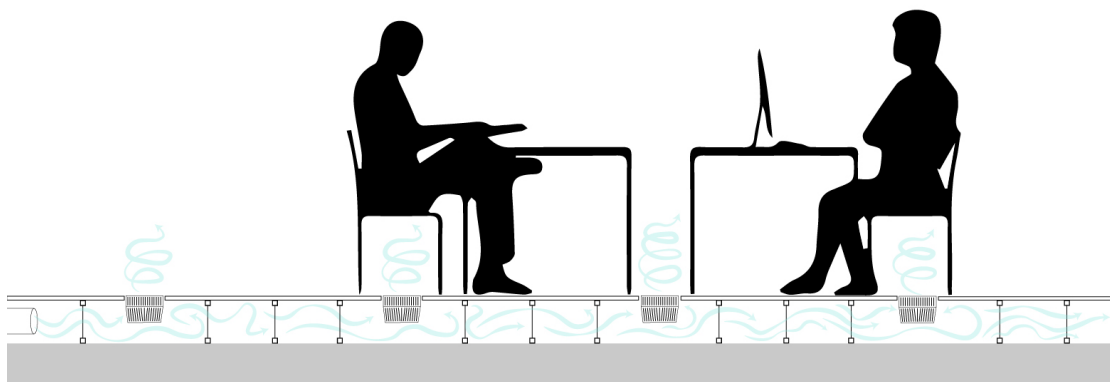
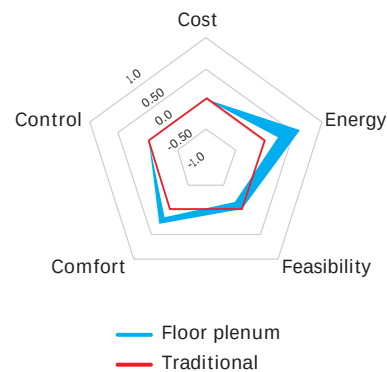


Figure 20. Scheme of a floor plenum air distribution system.

Ring ductwork is easier to produce and to install. The uniform pressure makes it easy to adjust and to control and it can be designed as a low-pressure system with low fan energy.

3.3.c | Ring systems

Ring systems differ from traditional systems due to the special structure of the ductwork. In fact, regular ductworks have a so-called “branched” structure, where lateral ramifications stem from a main duct or shaft with decreasing dimensions (and decreasing pressure) until the terminals are reached and the air is released in the rooms. In branched system, air always flow in the same direction and through predefined paths. On the contrary, ring systems are constituted by large circular ducts with constant dimensions, with smaller lateral ramifications directly leading to the room terminals.

Similarly to floor- and ceiling-plenums, ring systems are characterized by an almost constant pressure distribution. The air does not flow with a predefined route, but it can adjust to

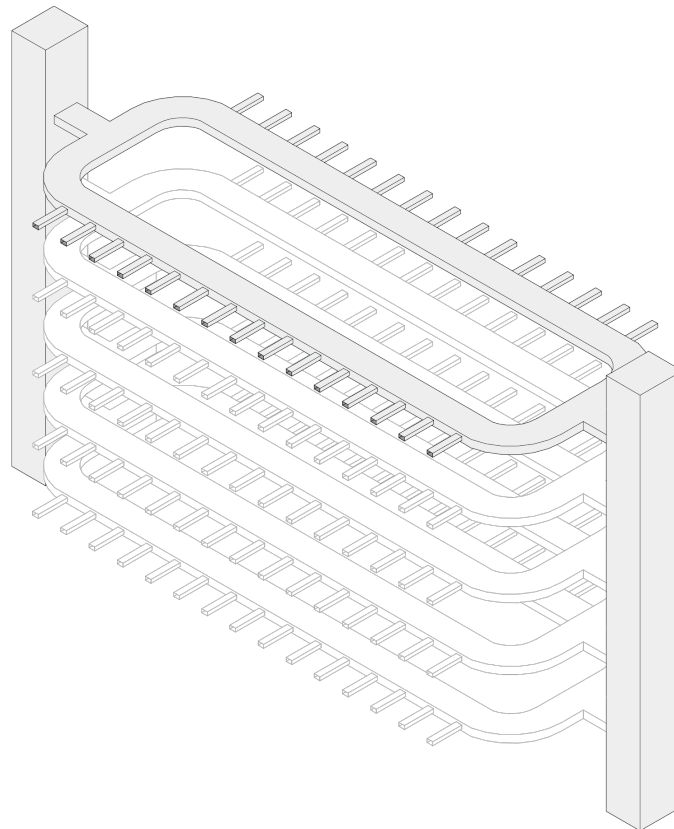
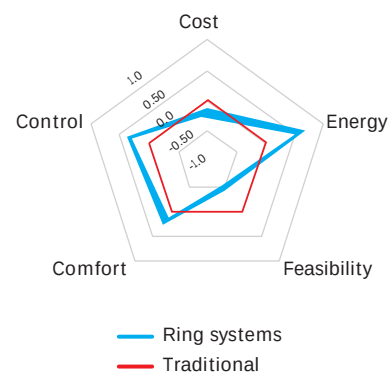


Figure 21. Scheme of ring ducting system.

Substituting **dampers** with small, high-efficiency fans, can reduce the fan energy consumption by 30%!

the lowest-resistance path.

Figure 20 gives an impression of a ring system. This low-pressure design concept has a number of advantages over a traditional branched ductwork:

- The uniformity in size of the ducts and branches makes it easier to produce and install;
- The more or less uniform pressure differences over the system makes it easy to adjust and control;
- The system can be designed as a low pressure system with less fan energy;
- The system has a high level of flexibility as long as the total air volume for the whole building is not exceeded.

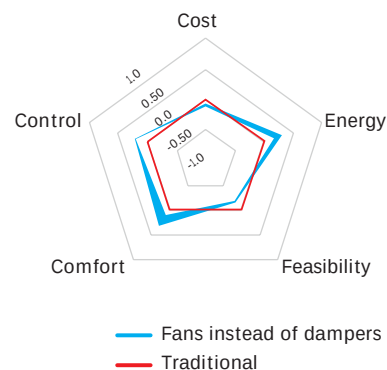
The system has some disadvantages compared with a conventional branched system:

- The construction needs more ductwork. This drawback should be compensated by the reduced production and installation costs;
- The system requires more space in the building which can lead to somewhat bigger floor heights;
- The system requires a clear structure and needs to be implemented in the first design phase, as the ductwork is not “as flexible” as usually presumed by the architect;
- For the design calculations there are no well described standard guidelines, procedures and software programs.

3.3.d| Fans instead of dampers

In conventional ventilation systems, regular dampers introduce pressure drops in the ductwork in order to control the airflow.

In order to reduce the total pressure drop of the ventilation system, thus decreasing the fan energy consumption, dampers can be replaced by miniature, low-energy fans and airflows can be controlled by adjusting the speed of the rotor. In this way, the main fan does not need to be dimensioned for the total pressure drop in the entire duct system – but only for the branch with the lowest pressure drop. Hence, the energy demand is reduced.



The decentralised fans supply the exact flow rate required to overcome the pressure drop in their branch. To ensure a correct airflow rate and high fan efficiency, the fans need to be appropriately dimensioned and integrated. These steps are crucial to lower the energy demand of the

ventilation system. Experiments [6, 7], both in laboratory and real buildings show that the theory is conform to the measurements. If the main fan and the decentralised fans have the same efficiency, 30% of the energy is saved.

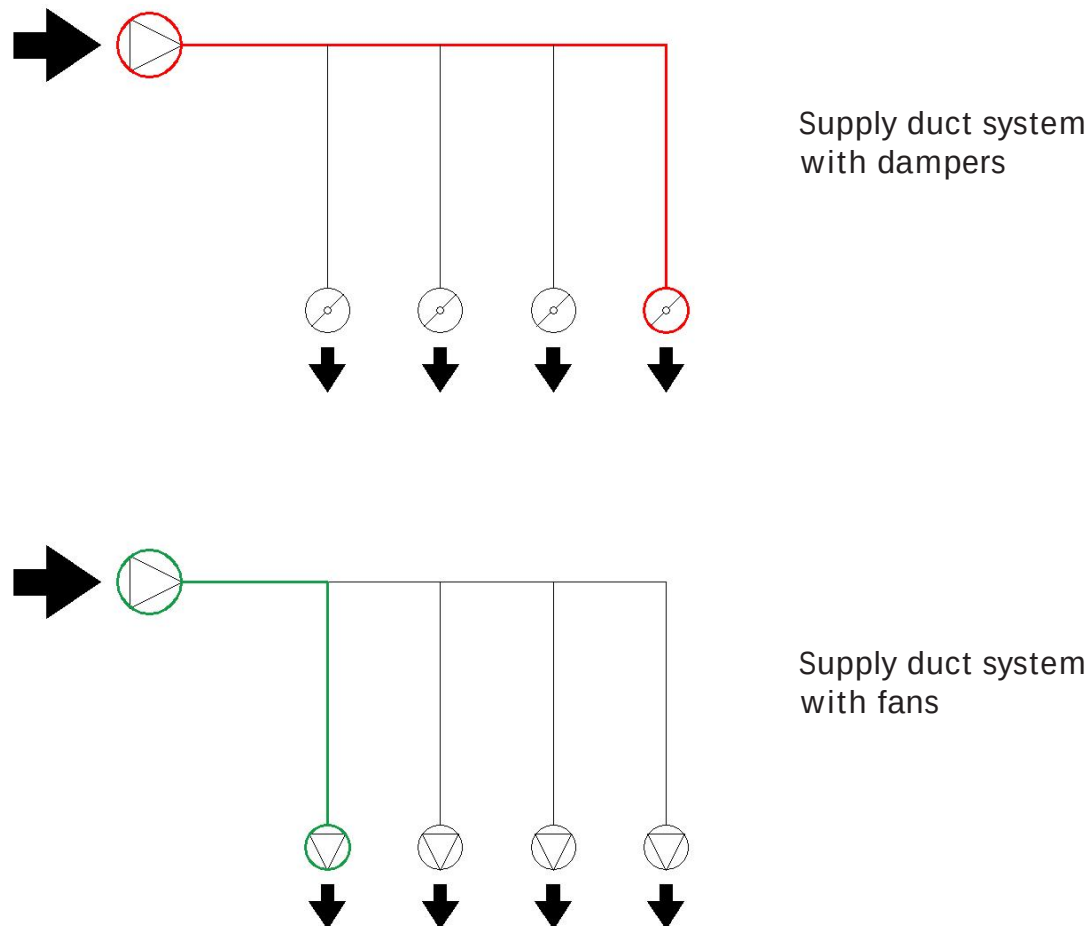


Figure 22. In the top image a traditional ventilation system with dampers is schematized; in this case, the fan needs to compensate for the pressure loss of the highest-resistance path. In the bottom image, dampers are substituted with small high-efficiency fans; in this case the main fan needs to compensate for the pressure loss of the lowest-resistance path.

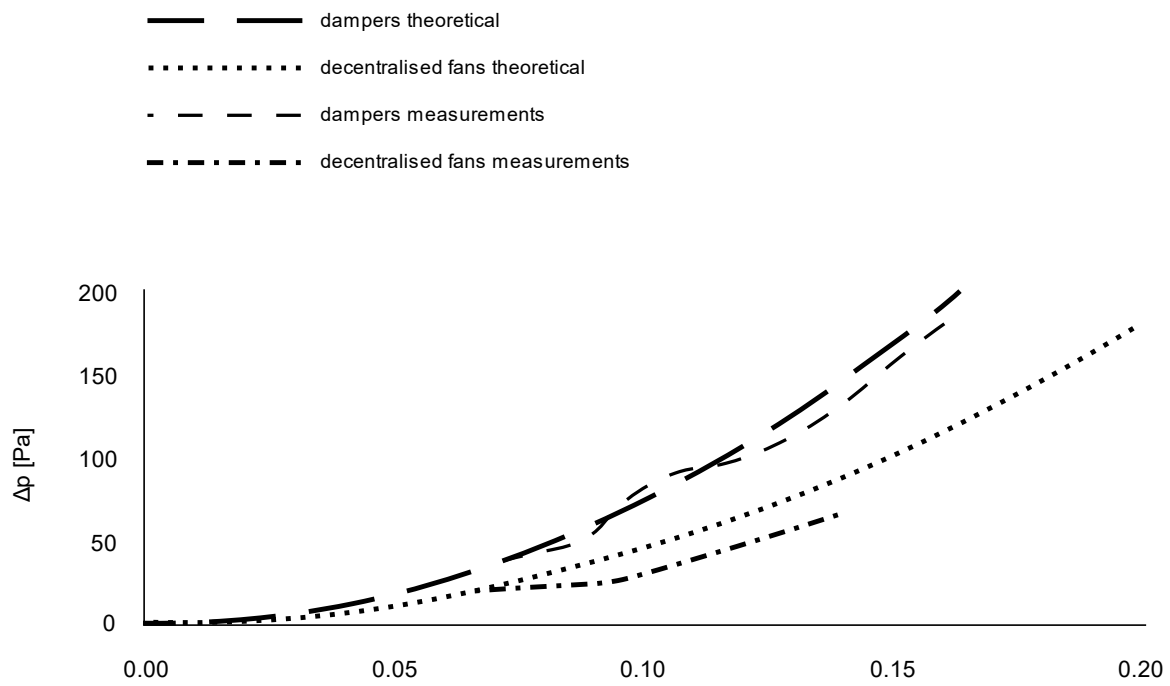


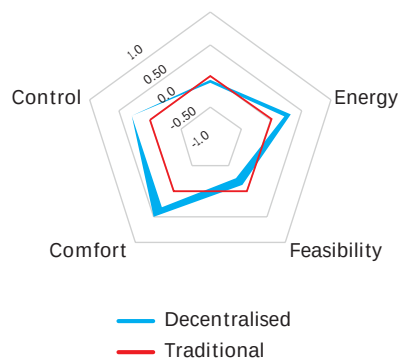
Figure 23. This graph shows the potentials of pressure reduction of a system that uses small fans instead of the traditional dampers at the terminals [6, 7].

A **decentralized ventilation** system offers several advantages if compared to a traditional, centralised system, including simpler control, more energy savings, lower pressure and the possibility to take advantage of natural forces, such as wind.

3.3.e| Decentralised ventilation

In traditional mechanical ventilation systems, the air is distributed to the whole building by one (or few) central AHU and a ductwork.

The concept of decentralised ventilation (DV) is to eliminate the central AHU and to place several, smaller AHU within each conditioned space, thus removing also most extension of the ductwork.



A DV unit consists of three main components: a compact decentralised AHU, an installation box and air distributors.

The compact decentralised AHU is equipped with an air filter, a small fan and a small heat exchanger that is hydronically connected to a cooling or heat source.

Dampers can function as filters to lower the noise from the outdoor environment and the fan.

All these components are placed in an installation box that is incorporated

near the facade or inserted in the floor or ceiling.

The choice for a decentralised ventilation system can be based on several advantages over centralised ventilation [17]:

- a shorter air travel distance is achieved with decentralised systems. This results in a reduction in ductwork, which has two positive effects: a reduced pressure loss in the duct system and the saving of construction volume in buildings. For example, if DV saves 30 cm per floor in a multi-story building, a volume equivalent to approximately 1 extra story could be saved for every ten built;

- individual zoning control;

- wind pressure on the façade can be used for reducing fan energy;

- the simplification of individual zoning control.

Fan speed, air flow rate and conditioning only depend on the intended zone where the installation box is located and can easily be adapted;

- smaller air flows and there less reheating energy required.

Of course, DV has also several limitations such as:

- the air treatment is not as extensive as in central AHU and maintenance is more

expensive and complicated;

- DV normally gives more noise disturbance than a well-designed central ventilation system;

- taking outside air from the façade, which has high thermal boundary layer, means to supply high thermal loads in summer;

- odors and waste gases steaming from neighbor or cars etc. are more easily taken from the façade compared to centralized ventilation units.

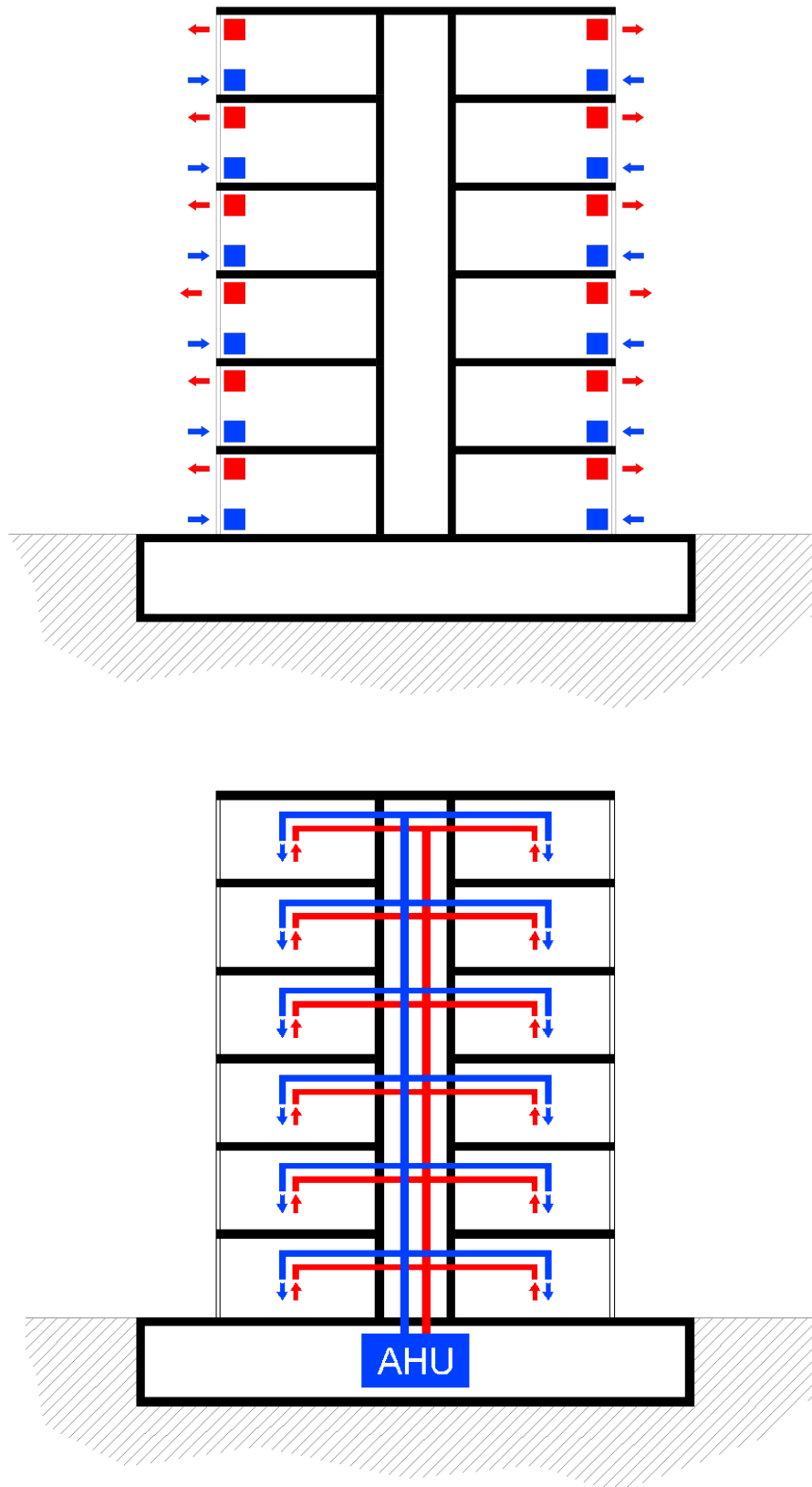


Figure 24. Top: scheme of a traditional centralised ventilation system. Bottom: scheme of a decentralised ventilation system

Hybrid ventilation

04

A **hybrid ventilation** system combines the best aspects of natural and mechanical ventilation: intelligent natural ventilation, if appropriate and efficient mechanical ventilation, if required.

04| Hybrid ventilation

The indoor environment in many buildings is increasingly being seen as unsatisfactory because of poor air quality and temperature control and, importantly, lack of local control by the occupants [3, 4]. One of the main issues causing such discomfort is the fact that such buildings are not responsive to the local climate. Natural ventilation is often used for solving this problem but, as discussed in Chapter 1.3 this is not always a viable solution, because often unable to provide the required indoor air quality and thermal performance. Hybrid ventilation systems are a promising alternative. In fact, they combine the best aspects of natural and mechanical ventilation: intelligent natural ventilation if appropriate, efficient mechanical ventilation if required [26]. At different times of the day or season of the year, to provide good air quality and a comfortable indoor environment, while offering the opportunity to considerably reduce the energy consumption. Hybrid ventilation systems are in the framework of IEA 35 [3, 4, 24] defined as:

“Systems providing a comfortable internal environment using different features of both natural ventilation and mechanical systems at different times of the day or season of the year. It is a ventilation system where mechanical and natural forces are combined in a two-mode system. The main difference between conventional ventilation systems and hybrid systems is the fact that the latter are intelligent systems with control systems that automatically can switch between natural and

mechanical mode in order to minimise energy consumption and maintain a satisfactory indoor environment.” [12]

As for natural ventilation, hybrid ventilation is based on a different design philosophy, therefore expectations about its performance cannot be the same as for mechanical ventilation. This does not mean lower standards nor higher costs. Also, it must be kept in mind that because of the different design approach, and therefore the different balance between capital, running costs, maintenance and disposal costs, cost comparisons between hybrid and mechanical ventilation systems should be done on a life-cycle-cost basis rather than simply on an initial capital cost basis [3, 4].

The main motivation for developing hybrid ventilation concepts is a clear demand for ventilation systems that are felt more natural by the occupants. The ductwork should be invisible and the air should flow into the building as naturally as possible. To reduce the electrical energy is more important now than before when the focus was on reducing the heating and cooling energy. Typically, energy consumption of fans is now about 30 to 50 % of the total energy consumed by an air-handling unit, when the system includes an efficient heat recovery device [8].

There is a whole range of hybrid ventilation strategies and it is not straightforward to attempt a classification. As shown in the scheme in Chapter 1.4, in this context, two categories will be considered following what proposed by [12]:

- 1) Two-mode systems: switching in time between natural ventilation and mechanical ventilation;
- 2) Mixed-mode systems:
 - mainly a natural ventilation system but with support of mechanical ventilation (fan assisted) if the pressure differences are not enough;
 - mainly a mechanical ventilation system, but whereby the available natural forces are optimally used.

The difference between the two typologies is that two-mode schemes require two fully autonomous installations of a natural and a mechanical system, and mixed-mode systems operate by natural ventilation and a helping fan. It must be kept in mind that the differences among the proposed categories are relatively blurred and often combinations among different systems can occur. A special kind of hybrid ventilation is also presented in Chapter 4.4, namely the Earth, Wind and Fire concept.

One last important aspect that must be kept in mind when addressing hybrid ventilation systems is that the contribution from natural driving forces (e.g. wind and stack effect) is responsible for only 1% of the energy savings compared to traditional mechanical ventilation systems, while the remaining 99% is just due to the reduced flow resistance, inherent with the hybrid ventilation design. For this reason, hybrid systems can also be considered as very low-pressure systems [21].

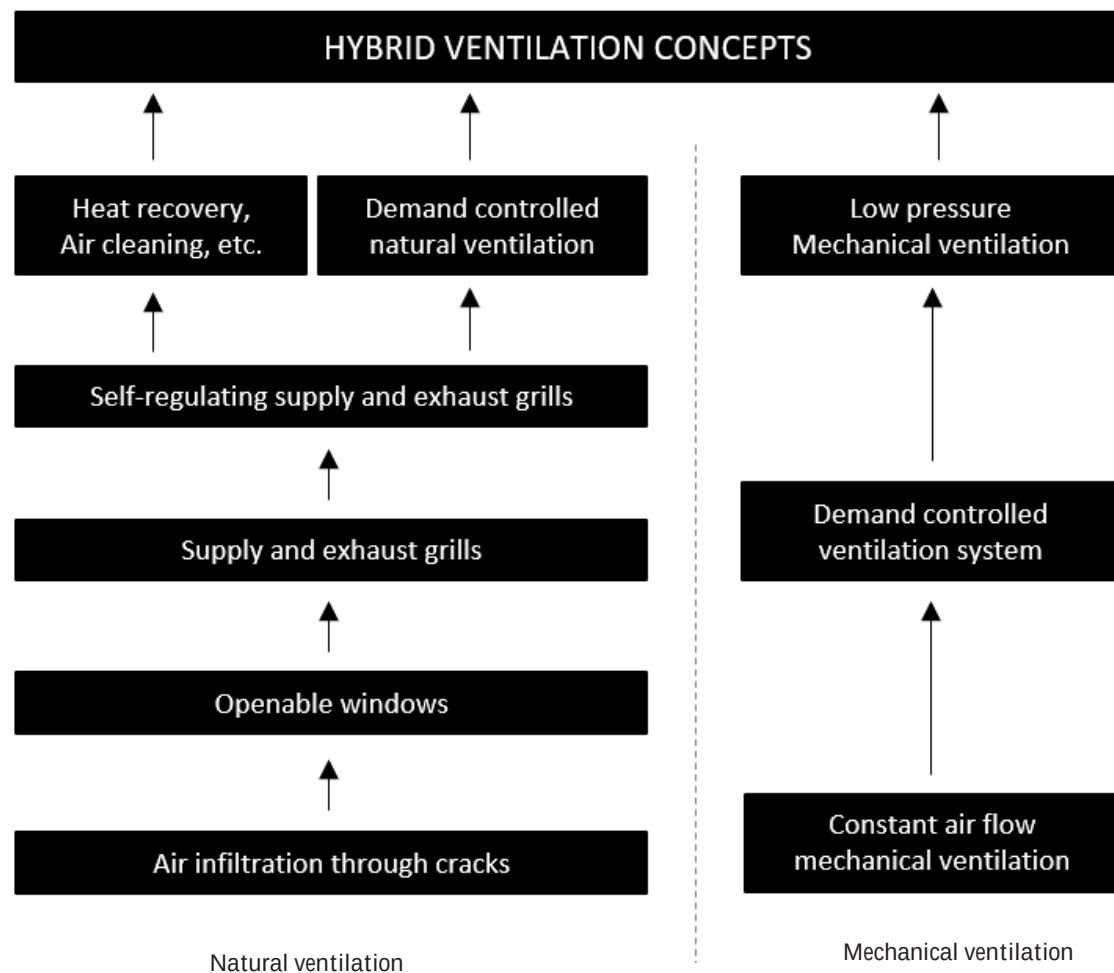


Figure 25. Characteristics of a mechanical ventilation system and of a natural ventilation system combined into hybrid ventilation [26].

Wind and stack effect
are the main **natural forces**
used in hybrid (and natural)
ventilation concepts.

It is possible to make use
of the **architectural features** of the
building for exploiting such forces:
elements such as atria, stairwells
and roofs can become integral parts
of the ventilation strategy.

4.1| Natural driving forces for ventilation

Hybrid ventilation systems make use of natural driving forces together with mechanical forces. The natural forces which are exploited for ventilation are mainly the wind pressure on the building façade or through dedicated devices (e.g. wind towers, wind

catchers) and the buoyancy force generated by temperature differences (e.g. stack effect in atria and solar chimneys).

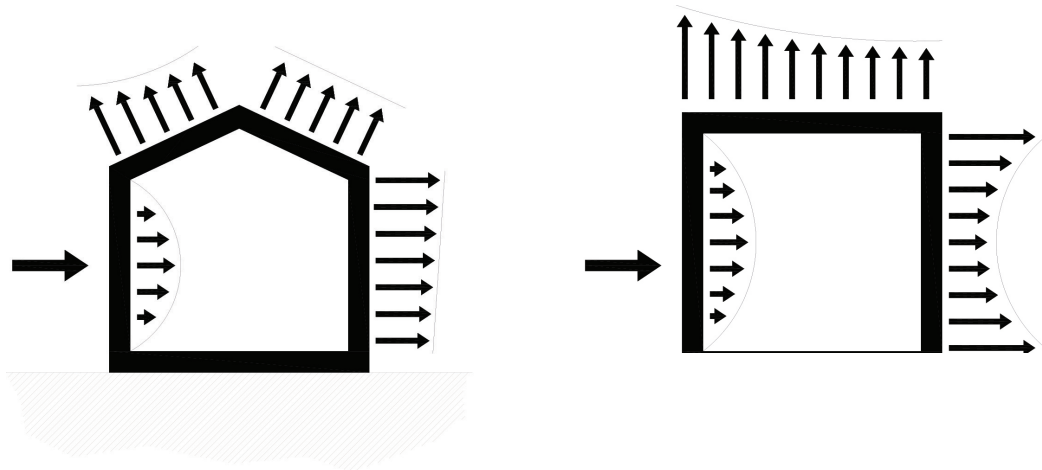


Figure 26. Top: scheme of the pressure distribution on the building envelope caused by wind. Bottom: a windcatcher.

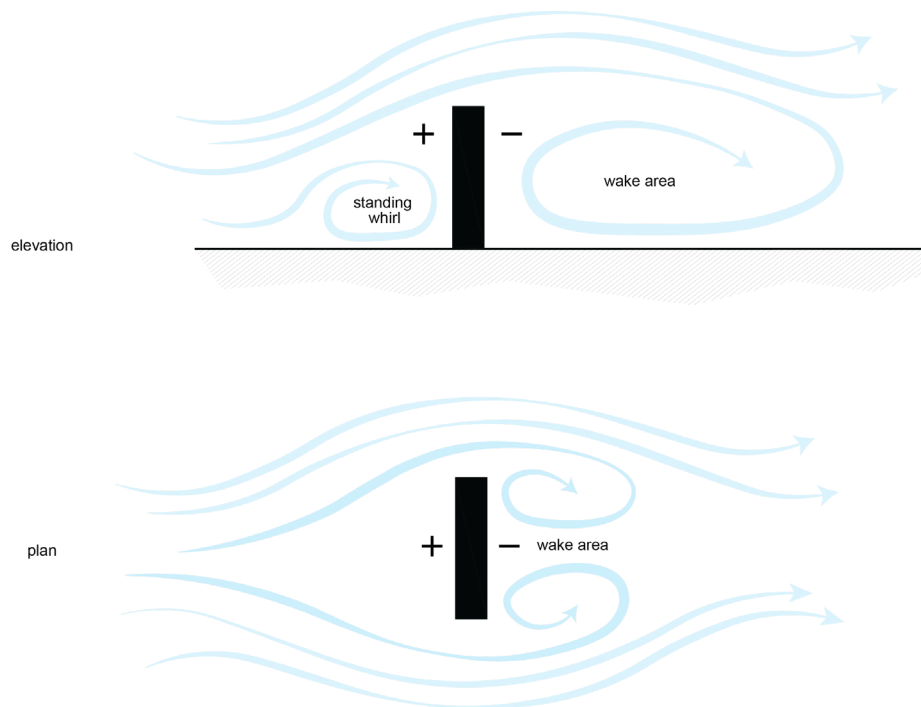


Figure 27. Wind-flow pattern around a tall building with positive pressure in front and negative pressure in the wake. Top: lateral view. Bottom: top view.

Wind

When an airflow hits any solid body, a region of high pressure is formed in the upwind side and a region of low pressure (also called “wake”) is formed in the downwind side of the body. When wind hits a building, the same phenomenon takes place (see Figure 25 top and Figure 26).

In Chapter 1.1 it was explained how air tends to flow from high-pressure to low-pressure zones.

When openings are placed on the building façade, this pressure difference can be used as driving force for ventilation.

Of course, wind does not blow constantly from the same direction and with the same intensity, which makes the driving force vary in time. For this reason, it is no easy task to design a hybrid or natural ventilation system that relies on wind and specific knowledge about climate and wind-building interaction is required.

In particular it is important to know:

- the local wind climate, namely how wind speed and direction changes through the year, for instance by using wind statistics from the nearest meteorological station, often publicly available;
- the local wind patterns, namely how the wind interacts with the existing surrounding buildings;
- the expected pressure distribution on the new building, determined by the interaction of the wind with the new building in its context. This can be done with simple rule of thumbs (normally described in the building codes) or with advanced computer simulations (CFD) or wind-tunnel experiments, depending on the importance of the project and the budget availability.

In this way, the shape and orientation of the building can be adjusted and openings can be smartly placed in the best locations in order to enhance the wind ventilation. The following recommendations should be followed:

- the building location should be at a distance from other buildings, namely it should not be in their wake so that they will not shelter it from summer winds.

- airflow paths transporting dust and pollutants must be avoided

- the building should be positioned and oriented in order catch prevailing summer wind direction. If the prevailing winter wind direction is different from the summer one, as is usually the case, it is possible to optimise the location of the building in order to obtain a good summer wind exposure, while sheltering the building from cold winter winds [10]

- in very dense urban areas, spaces most needing ventilation should be put on the highest floors where wind flows is stronger and less turbulent than near the ground

- the effect of wind forces can be enhanced by the use of wind catchers, roof cowls or wind towers with openings controlled by a weather station. It is expected that the ventilation flow rate can increased by up to 30% [1]. Such elements must be designed to ensure negative pressure at the outlet openings and positive pressure at the intake for all wind directions both to enhance the natural driving forces but also to avoid backflow in the system.

- supply air to the rooms should happen through the façade rather than via ducts and corridors and staircases should be exploited as air distribution paths for exhaust air – or opposite.

The **shape** and **orientation** of the building can be adjusted and **openings** can be smartly placed in the best locations in order to enhance the wind ventilation. This implies knowledge of the local **wind climate**.

Temperature differences in large atria and stairwells create **stack effect**, which can be exploited for promoting ascendant air movements.

Solar chimneys can also be added to the building for enhancing this phenomenon.

The building itself can become integral part of the ventilation strategy.

Stack effect

Stack effect or chimney effect is the movement of air into and out of buildings resulting from air buoyancy. Buoyancy occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences. The result is either a positive or negative buoyancy force. The greater the thermal difference and the height of the structure, the greater the buoyancy force, and thus the stack effect. The stack effect helps drive natural ventilation and air infiltration. The higher the vertical extension of

the space, the stronger the stack effect is. Tall atria and stair halls are particularly suited for creating stack effect. Solar chimneys are special architectural elements consisting of a long, vertical shaft where solar radiation is captured (e.g. with an external glass surface letting sun radiation in and an internal dark adsorbent surface which collects sun energy and increases its temperature); such devices can maximise stack effect for natural ventilation purposes.

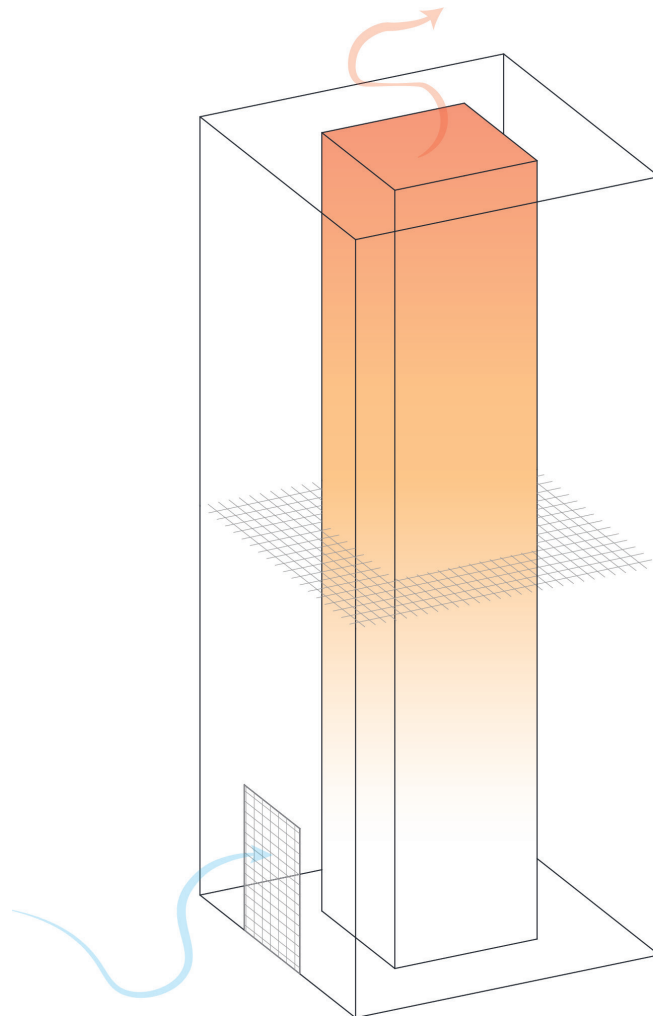


Figure 28. Scheme of the stack effect (temperature distribution) in a tall space, e.g. a stairwell or a solar chimney.

In a **two-mode system**, the ventilation strategy switches between natural and mechanical depending on the indoor comfort requirements.

During heating and cooling seasons, mechanical ventilation is preferred, while natural ventilation is allowed during shoulder seasons.

4.2| Two-mode systems: alternate natural-mechanical

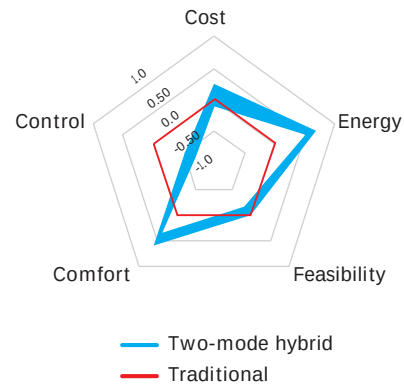
These hybrid ventilation concepts are based on the strategy of a switching in time between natural ventilation and mechanical ventilation.

Normally, during heating and cooling season the indoor comfort requirements are stricter and require more advanced control systems; for this reason, mechanical ventilation is preferred over natural.

On the other hand, during shoulder seasons when temperature and humidity levels are more temperate it is possible to switch to fully natural ventilation.

In this chapter, three concepts will be described following [8]:

- 1) System with mechanical exhaust
- 2) System with supply air ducts
- 3) Balanced ventilation system



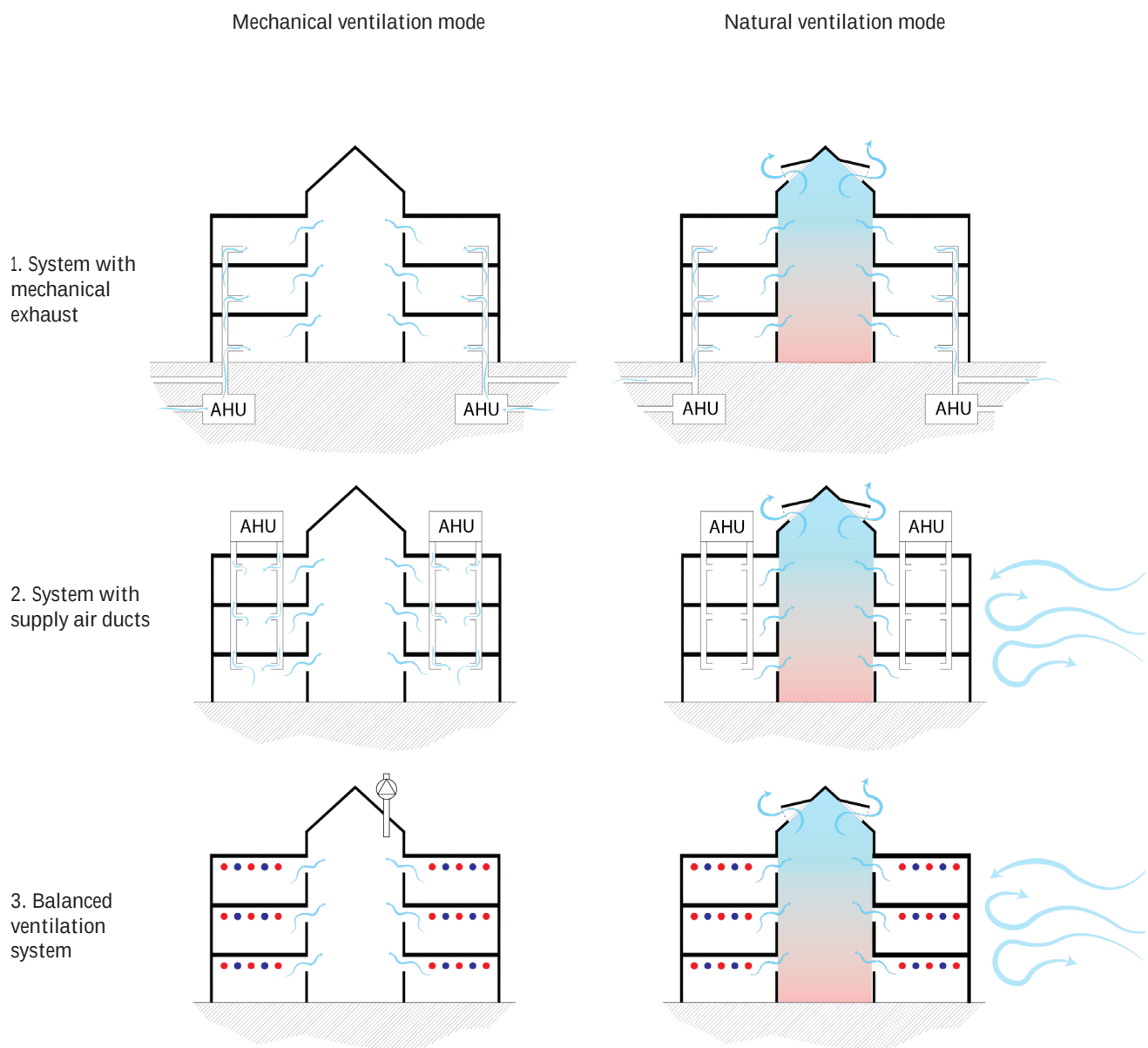


Figure 29. Two-mode hybrid ventilation systems. The left column schematises the mechanical ventilation mode. The right column schematises the natural ventilation mode.

System with mechanical exhaust

These systems operate partly naturally during the heating season by using natural forces such as stack effect and wind pressure on façade opening or on roof devices, while heating of the supply air is carried out locally with wall-mounted radiators. Supply air fan or ductwork are not necessary [2].

On the other hand, during cooling and mild climate period the ventilation is based on mechanical forces and window ventilation. It is recommended to control the airflow rate of each space with CO₂ and occupancy sensors, meaning that supply and exhaust air dampers are closed when the space is not occupied.

System with supply air ducts

In these systems, supply air is led into the building through air handling unit (AHU) only during heating and cooling season.

During mild climate season the supply air bypasses AHU and flows into the building naturally.

This means that there are two parallel supply air ducts from outside to the main ductwork: one with a fan, heating and cooling coils and air filtering, and the other without any air-handling or fan. The switch between the two supply air ducts is on the outdoor temperature.

Heating and cooling elements can be integrated in the AHU or in local supply-air room devices, or both. It is recommended to control the airflow rate of each space with CO₂ and occupancy sensors [8]

Balanced ventilation system

These systems use balanced mechanical ventilation during the heating and cooling seasons, namely with both mechanical supply and exhaust. During the mild weather, the supply air can be taken directly from outside to the perimeter zone of the building through walls or windows.

The ventilation is then based on window opening and mechanical exhaust system.

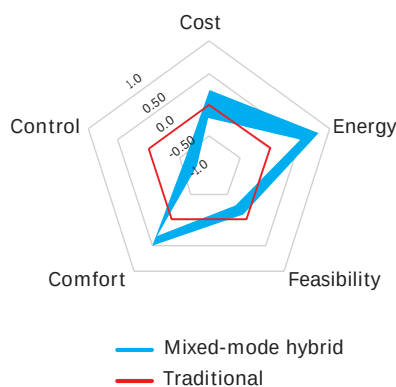
The control principles of airflow rates and indoor temperature are mainly the same as in the previous concepts.

A **mixed-mode system** is a natural ventilation system with backup mechanical components, e.g. an additional fan.

It is essentially a natural ventilation concept during the majority of occupied hours .

However, since natural forces are unpredictable, during periods of lack of the required pressure differences, or during periods of increased ventilation demands, a fan compensates by mechanically increasing the system pressure.

4.3| Mixed-mode systems: Fan -assisted natural ventilation and Stack-effect- and wind-assisted mechanical ventilation



This ventilation strategy is aimed to be essentially a natural ventilation concept during the majority of occupied hours. However, since wind and buoyancy are by nature not very predictable forces for ventilation, during periods of lack of the required pressure differences, or during periods of increased ventilation demands, a fan compensates by mechanically increasing the system pressure. In this strategy, when a ductwork distribution system is present it must be a low-pressure concept; a low-pressure fan can be applied which, if advanced control strategies are used, allows to make optimal use of the available pressure differences due to stack and wind effect.

This principle is mainly used in larger commercial buildings where the natural driving forces are inadequate in some periods. This hybrid solution is able to deal with larger variation of outdoor temperature and internal heat gains than can be accommodated by a purely natural ventilation strategy.

The result is that energy consumption is minimised under normal day-to-day conditions, while ensuring sufficient ventilation capacity under a wide range internal/external scenarios.

The following two categories of mixed-mode ventilation can be identified:

- Stack-effect- and wind-assisted mechanical: mainly a mechanical ventilation system, but whereby the available natural forces are optimal used
- Fan -assisted natural: mainly a natural ventilation system but with support of mechanical ventilation (fan assisted) if the pressure differences are not enough;

The following components can be found in mixed-mode ventilation systems [13]:

This solution is able to deal with larger variation of outdoor temperature and internal heat gains than purely natural ventilation. Energy consumption is minimised under normal day-to-day conditions, while ensuring sufficient ventilation capacity under a wide range internal/external scenarios.

- Low-pressure ductwork;
- Low-pressure fans with advanced control mechanisms such as frequency control, air flow control, etc...
- Low-pressure static heat exchangers and electrostatic air filters;
- Wind towers, solar chimneys or atria for exhaust;
- Underground ducts, culverts or plenums to pre-condition supply air.

For control of thermal comfort, indoor air quality and air flow, components can include:

- Manually operated and/or motorized windows, vents or special ventilation openings in the facade- and in internal walls,

- Room temperature, CO₂ and/or air flow sensors,
- A control system with weather station

The schemes below show some possible configurations of mixed-mode ventilation which are highly integrated into the building design:

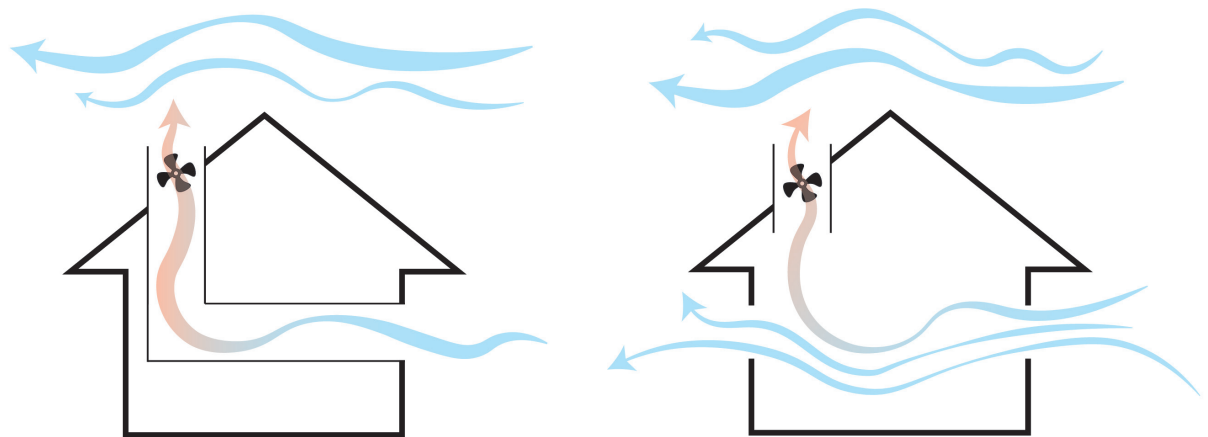


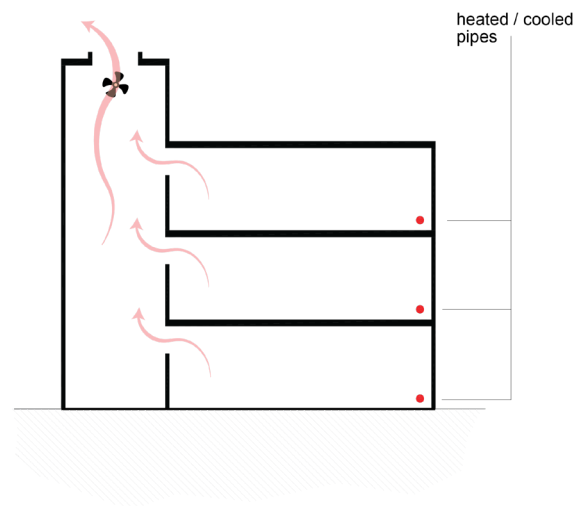
Figure 30. Left: scheme of a stack-effect and wind-assisted mechanical ventilation system. Right: scheme of a fan-assisted natural ventilation system.

Possible components of a mixed-mode ventilation system:

- Low-pressure ductwork;
- Low-pressure fans with advanced control mechanisms such as frequency control, air flow control, etc...
- Low-pressure static heat exchangers and electrostatic air filters;
- Wind towers, solar chimneys or atria for exhaust;
- Underground ducts, culverts or plenums to pre-condition supply air.
 - Manually operated and/or motorized windows, vents or special ventilation openings in the facade- and in internal walls,
- Room temperature, CO₂ and/or air flow sensors,
- A control system with weather station

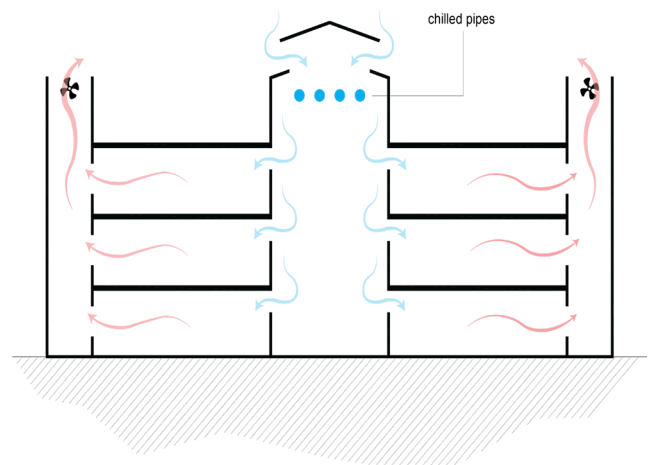
Fan-assisted stack

A large atrium is used as an exhaust airway with auxiliary fan. The air naturally flows through the façade and is locally heated and cooled. By stack effect, air is exhausted through the main atrium where an auxiliary fan helps in times of high demand or insufficient natural driving force.



Top-down ventilation

a wind tower draws air inside the main atrium that works as a distribution shaft towards all floors. The air is then exhausted in lateral shafts, where low-pressure fan eject it into the external environment.



Mixed-mode ventilation with embedded culvert and heat exchanger.

The concept is designed for maximum stack effect and for maximum responsive building integration. An embedded concrete duct leads the fresh air through an electrostatic precipitator, through the first heat recovery coil and distributes it to the floors to the diffuse ceiling ventilation system. The extract air flows from all floors via separate vertical ducts to the second heat recovery coil above the roof. Heat is transferred from the second coil in the exhaust to the first coil in the air intake. The recovery coils are linked with a pump-powered liquid loop.

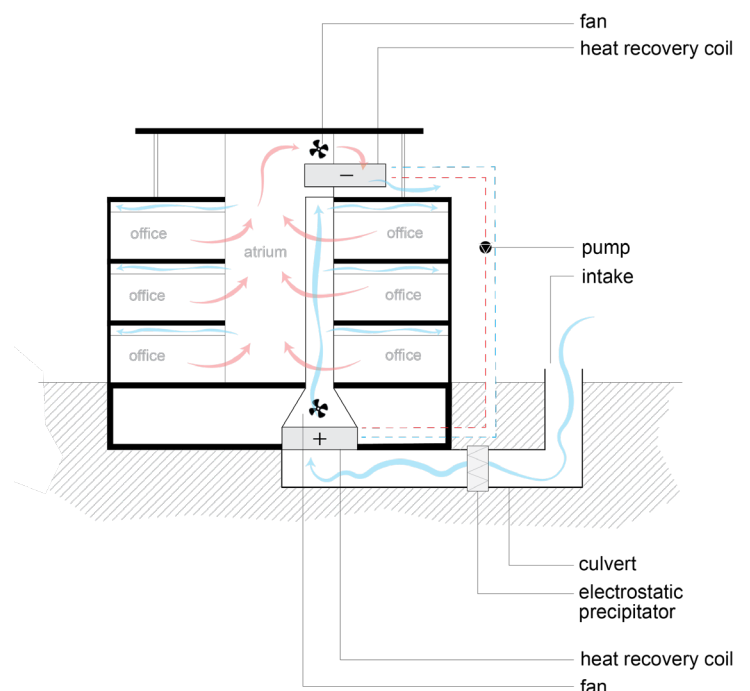


Figure 31. Schemes of different design solutions for a mixed-mode hybrid ventilation system.

Earth, Wind and Fire (EWF)

is a particular and innovative hybrid ventilation concept, which requires a high degree of architectural integration.

Fresh air is brought into the building by means of the **climate cascade**, a tall shaft where water droplets are continuously sprayed, dragging down and cooling the air.

On the building façade, a **solar chimney** releases the exhaust air into the environment exploiting the stack effect.

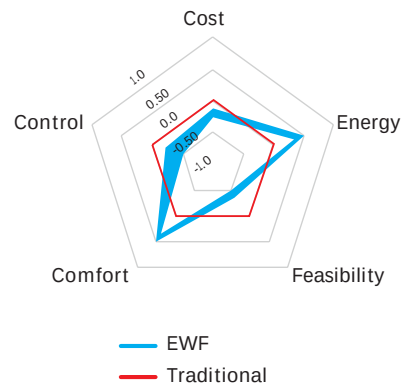
Backup fans, heaters and coolers and can be added to the system.

4.4| Earth wind and fire

Earth, Wind and Fire (EWF) is a special kind of hybrid ventilation. The core of the climate system is the Climate Cascade which is designed as an architectural shaft and performs as a gravity-activated heat exchanger for conditioning the ventilation air. Within the Climate Cascade, ventilation air is being cooled or heated, dried or humidified as needed. At the top, in summer and winter, water of approximately 130C is fed through nozzles and, by momentum transfer from droplets to air, the downward air movement from the over pressure room is enhanced. With this aerodynamic pressure, together with the hydraulic pressure and the downward thermal draft, fans become superfluous. The required cold is extracted from the soil, and heat is directly or indirectly supplied by the solar chimney. Because of the high heat transfer coefficient from the falling droplets to the air and the immense active surface of the millions of droplets in the spray spectrum, the Climate Cascade operates with a very minimal temperature difference between air and water.

Ventilation air is extracted through the Solar Chimney or Solar Façade in which solar energy is harvested to be exploited for heating the building during the heating season. With the assistance of a heat exchanger at the top of the solar chimney, the solar heat is transferred to circulating water and fed to the heat and cold storage in the soil under the building.

This technique is applied in horticulture for cooling and heating greenhouses. The thermal



performance of a solar chimney, which, at a certain building height, is mainly determined by the width of the chimney, is only minimally tailored to the exhaust volume flow at reference conditions. These are arbitrarily set at an outside temperature of 20°C and a radiation flux of 400 W/m². With the application of a proper type of glass, an annual efficiency of approximately 60% can be achieved. The total radiation on a south facing surface in the reference year NEN 5060:2008 is approximately 860 kWh/m² thus a yield of approximately 500 kWh per m² solar chimney may be expected. For the morphology of a solar chimney, numerous variants are conceivable in which the gable covering the Solar Façade yields the highest energy performance.

The airflow for the supply of ventilation air through the Cascade Climate and the exhaust, thereof, through the Solar Chimney or Solar Façade is caused by pressure differences. These are generated by density differences between colder and warmer air and are

CLIMATE CASCADE air supply

SOLAR CHIMNEY air exhaust

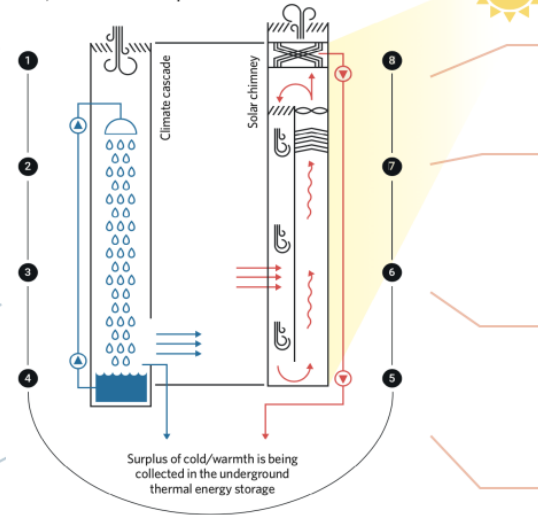
1) Outdoor fresh air is passively sucked in

2) Water sprinklers create pressure and downward movement

3) The air is cleaned and heated (in winter) or cooled (in summer)

4) Water is recirculated from the basin and heat/cold transferred to the ATES system

Earth, wind and fire concept



8) heat recovery unit

7) Space for PV panels or solar collectors

6) The sun warms the air and generates buoyancy with upwards movement

5) The air is exhausted to the solar chimney

Figure 32. Scheme of the Earth, Wind and Fire concept

proportionate to the height of the Cascade Climate and Solar Chimney or Solar Façade. Given the relatively minimal temperature and pressure differences, a certain minimum height of the building is necessary. The developed Earth, Wind & Fire concept should be considered a central facility for the air conditioning of buildings that can replace the central mechanical ventilation of a building. Decentralized facilities for heating and cooling at the workplace level such as climate ceilings, fan-coil-units, radiators, etc. can be combined excellently with the concept. As an alternative (or in addition to decentralized facilities) a small AHU can be placed at the bottom of the climate cascade for air post-treatment (dehumidification, post-heating and -cooling); backup mechanical fans are also placed at the intake or outlets of climate cascade and solar chimney for compensating during periods of low pressure difference (e.g. low sun radiation or low outdoor temperature).

Although not intended for use in residential buildings, several elements can also be of use in apartment complexes. The Earth, Wind & Fire concept is a total concept. This does not mean that the responsive elements in the developed study can only be used in combination. A stand-alone application of a Solar Chimney and Solar Façade or Cascade Climate in office buildings is quite feasible. The Earth, Wind & Fire concept can be applied in any architectural style including classic, modern, international, postmodern, bioclimatic, etc. It is the architect who shapes the development of the building as a climate machine. New construction can dedicatedly be designed on the basis of the

Earth, Wind & Fire concept. In the event of significant renovations of existing buildings, the concept may also be applied either in part or in its entirety. A Solar Chimney is a possible additions to a building, and existing facades can be converted into Solar Facades. Existing installation shafts can be converted to Climate Cascades as indicated in a performed case study.

This aspect may also play a role in the choice between demolition or renovation of existing buildings. It is often intuitively decided to renovate, but research indicates that renovation in relationship to environmental performance is not always an obvious choice [28].

04| Conclusions

The objective of this booklet is to provide design advices on how to reduce the fan energy in traditional and hybrid ventilation systems and to show how the problem can be addressed with a holistic design approach, integrating low-pressure systems in the building design. Direct design examples have been provided, together with more theoretical principles. With this information at hand, architects, engineers and constructors should be sufficiently equipped for understanding the importance of designing buildings with low-pressure ventilation systems, with a high degree of integration between the ventilation strategy and the building itself. The authors' hope is that by disseminating this information, the design of low-pressure ventilation systems will become common practice.

A | Focus: components of a mechanical ventilation system

This appendix is an extension of Chapter 2. for each component, a more detailed description is provided, including information on the most typical pressure drop caused by the component in the ventilation system.

A.1 | Detailed descriptions of system components

Filters

Air filtration is almost always present in ventilation systems. Filters have two main functions:

- cleaning the supply air from dust and particles
- protecting the AHU components from soiling (especially the heat exchanger and the fan).

Filtration is therefore typically placed first in the AHU. Most commonly used air filters are bag filters and electrostatic filters.

- Bag filters are composed by glass fibre or plastic material. They can have an additional layer of active coal, which is recommended in areas with traffic pollution. Bag filters are divided into fine filters (capturing particles of less than 1 micrometer) and coarse

filters (capturing particles larger than 1 micrometer). Contaminating particles from the air streams are kept by bag filters.

After several time, the filters are so polluted that a large pressure drop occurs which increases the need for replacement. Bag filters cause a pressure loss of around 100Pa in unused condition and 250 Pa when they need to be replaced [20]. The pressure loss also depends on the density of the mesh filters and the outdoor environment. It is recommended to find out the filter changing frequency using calculations from the filter vendor. By increasing the filter surface, the pressure drop can be limited to 30 Pa..

- Electrostatic filters (or precipitators) have generally lower pressure drops than bag filters and therefore are more energy efficient. Despite they are highly effective for removing small particles, they let large particles

pass. They are less likely to harbour bacteria, compared to bag filters, but they can produce toxic ozone and NOx.

Heating and cooling elements

AHU's may need to provide heating, cooling, or both to change the supply air temperature, and humidity level depending on the location and the application. Such conditioning is provided by heat exchanger coils within the AHU air stream. The most common heat exchangers are coils constituted by copper tubes where hot or chilled water flows and copper or aluminum fins to aid heat transfer. Cooling coils will also employ eliminator plates to remove and drain condensate.

If dehumidification is required, then the cooling coil is employed to over-cool to that the dew point is reached and condensation occurs. A heater coil placed after the cooling coil re-heats the air (therefore known as a re-heat coil) to the desired supply temperature. Due to this high concentration of pipes and fins, the heating and cooling coils constitute (together with the heat recovery device, see later) is one of the largest flow resistance in the system.

Heat recovery device

A heat recovery device is a heat exchanger fitted to the air handler between supply and extract airstreams. This allows to "recycle" part of the heat of the exhaust air by transferring it to the supply air. In order to do this as efficiently as possible, a large contact surface between the two airflows must be guaranteed, which normally is achieved with the use of two common types of heat exchangers:

- plate heat exchangers: sandwiches of plastic or metal plates with

interlaced air paths;

- thermal wheels (or rotary heat exchanger): slowly rotating matrices of finely corrugated metal, operating in both opposing airstreams. When the air handling unit is in heating mode, heat is absorbed as air passes through the matrix in the exhaust airstream, during one half rotation, and released during the second half rotation into the supply airstream in a continuous process.

In both devices, the air is forced through a myriad of small passages, leading to a large pressure drop. Together with the heating and cooling coils, the heat recovery device is one of the largest flow resistance in the system. Heating and cooling elements

AHU's may need to provide heating, cooling, or both to change the supply air temperature, and humidity level depending on the location and the application. Such conditioning is provided by heat exchanger coils within the AHU air stream. The most common heat exchangers are coils constituted by copper tubes where hot or chilled water flows and copper or aluminum fins to aid heat transfer. Cooling coils will also employ eliminator plates to remove and drain condensate.

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Humidifier

Humidification is often necessary in colder climates where continuous heating will make the air drier, resulting in uncomfortable air quality and increased static electricity. Various types of humidification may be used:

- Evaporative: dry air blown over a reservoir will evaporate some of the water. The rate of evaporation can be increased by spraying the water onto baffles in the air stream.
- Vaporizer: steam or vapor from a boiler is blown directly into the air stream.
- Spray mist: water is diffused either by a nozzle or other mechanical means into fine droplets and carried by the air.
- Ultrasonic: A tray of fresh water in the airstream is excited by an ultrasonic device forming a fog or water mist.
- Wetted medium: A fine fibrous medium in the airstream is kept moist with fresh water from a header pipe with a series of small outlets. As the air passes through the medium it entrains the water in fine droplets. This type of humidifier can quickly clog if the primary air filtration is not maintained in good order.

Apart from the wetted medium type, humidifiers do not constitute a considerable flow resistance.

Silencers

The blower in the air handler generates noise, which should be attenuated before ductwork enters a noise-sensitive room. To achieve meaningful noise reduction in a relatively short length, a sound attenuator (or silencer) is used. There are two kinds of silencers:

AHU silencers and duct silencers. The first ones are placed directly into the AHU for reducing the fan generated noise: silencers with internal baffles can achieve pressure drop of 50 to 100 Pa, which is unnecessarily energy intensive. Duct silencers are a specialty duct accessory that typically consists of an inner perforated baffle with sound-absorptive insulation to reduce the noise generated by air turbulence before it is introduced into the rooms; these sort of silencers lead to smaller pressure drop, but they need to be chosen carefully with the correct dimensions.

Outlets

The outlets are the terminal sections of the exhaust duct system, responsible to discharge the exhaust air into the environment, while preventing short-circuiting effect, namely direct recirculation of stale and contaminated air into the supply system.

One option to ensure the best performances is to locate the outlets as far as away from the inlets as possible, but often this is not done either because of a lack of space, either because of poor design strategies. More often, outlets are designed as jet stacks, providing high-velocity exhaust flows in order to prevent recirculation.

However, this strategy is energy consuming: jet roof stacks can lead to a pressure drop up to 100-175 Pa and an increase of the specific fan power up to 0.2 kW/(m³/s) [21].

Ductwork

In traditional mechanical ventilation systems, the supply and exhaust air (or just one of the two) moves from the AHU to the space and vice versa via a system of ducts. Most of the

times, the duct system consists of a main branch, or shaft, and a series of lateral ramifications that supply and collect air uniformly through the ventilated spaces. The design of the duct system has a considerable impact on the overall performance of the ventilation system and its energy consumption.

Poor design can cause high pressure losses up to 150 to 280 Pa for each supply and exhaust side [21, 1, 14].

Normally, a duct path with the greatest pressure drop can be identified; this is called the “critical path” and it is the one which determines the total pressure drop of the network. Changing the ductwork design along the critical path to reduce its pressure drop may change the critical path to another segment of the network. This means that the optimization of the duct network is an iterative, trial-and-error process, which requires experience and dedicated software.

Terminals

Air terminal devices are grilles or diffusers at the end of the duct system, which distribute and mix supply air into the ventilated spaces. Their design the air speed strongly affects their pressure drop.

Fan

AHU typically employ a large squirrel cage blower driven by an AC induction electric motor to move the air. The blower may operate at a single speed, offer a variety of set speeds, or be driven by a variable-frequency drive to allow a wide range of air flow rates. Flow rate may also be controlled by inlet vanes or outlet dampers on the fan.

Multiple blowers may be present in large commercial air handling units, typically placed at the end of the

AHU and the beginning of the supply ductwork (therefore also called “supply fans”). They are often augmented by fans in the return air duct (“return fans”) pushing the air into the AHU. The components which are listed above are the main sources of flow resistance in the ventilations system, which altogether produce are pressure drop depending on the flow rate. The fan(s) needs to overcome such pressure drop, consuming energy in order to allow the air to continuously flow through the AHU and the ductwork. Counterintuitively, the fan itself can be responsible for a large part of the total flow resistance of the ventilation system. In fact, when the fan is not properly dimensioned or is wrongly placed into the AHU, turbulence and swirls can be generated right at the entrance and exit of the fan. This aerodynamic inefficiency (normally called “system effect”) causes a very large pressure drop and it could virtually be the largest source of flow resistance in the whole system, up to more than 350 Pa. For this reason it is of paramount importance to choose the right fan and design its casing as aerodynamic as possible.

A.2 | Pressure loss in ventilation system components

The AIVC Technical note 65 “Recommendations on Specific Fan Power and Fan System Efficiency” concludes that the total pressure loss through ventilation systems is roughly shared equally between the air handling unit and the distribution system. This means that it is equally important to act both sides in order to reduce the total flow resistance and, in turn, the fan energy consumption.

Figure A1 shows an example of aggregating component pressure drops through a ventilation system in a large building at design flow rate [24]. The case of a poor design and a good design are compared.

A number of observations can be made:

- the largest pressure drops are due to aerodynamic inefficiencies of the fan itself. This can be interpreted as a wrong placement of the fan or a wrong choice of the fan model. In a good design, this pressure drop can be completely removed;
- filters, heat exchangers and silencers are also offering a large flow resistance, which can be drastically reduced with a good system design
- the AHU outlet, when not optimally design, can also cause a large pressure drop, which is reduced more than tenfold with a good design;

- surprisingly the ductwork itself, although it is the longest and most complex path the air goes through, does not provide the largest pressure drop, nor it can be considerably improved with a good design.

			Poor design [Pa]	Good design [Pa]
supply	Distribution	Inlet	70	25
	AHU	Filter	250	50
		Heat exchanger	250	100
		Heating coil	100	40
		Silencer	200	0
	Aerodynamic inefficiencies (fan)		360	0
	Distribution	Ductwork	150	100
		Terminals	50	30
return	Distribution	Terminals	30	20
		Ductwork	120	80
	AHU	Silencer	100	0
		Filter	250	50
		Heat exchanger	250	100
	Aerodynamic inefficiencies (fan)		360	30
	Exhaust duct + outlet		250	20
AHU		sum	1400	340
Distribution		sum	1390	305

Figure A1. Example of pressure drop for each component of a conventional mechanical ventilation system. The table shows the example of a poor design and a good design [24].

Appendix

B

Recommendations for air filters

- Determine the filter based on local air quality. Sometimes filters may not be necessary.
- Place the air intake away from sources of pollution (e.g. streets) in order to reduce the need for filters.
- A fine filter on the supply side and one the exhaust side might be sufficient.
- Use bag filter with low air speed and large surface area.
- Use electrostatic precipitators
- Determine the filter changing frequency and change the filter when needed
- When a best practice for cleaning the ventilation system is in place, the exhaust-side filter can be avoided
- Avoid to place a coarse and a fine filter in series. It is not a cost-effective solution and it will increase the pressure drop.

B | Optimised mechanical ventilation systems: recommendations for each component

The main two objectives of filter are: removing outdoor pollutants like pollen and traffic soot and protecting heat exchangers and the whole duct system from soiling.

B.1| Filters

The main two objectives of filter are: removing outdoor pollutants like pollen and traffic soot and protecting heat exchangers and the whole duct system from soiling.

The most conventional filtering system in mechanical ventilation are bag filters, which are highly effective and inexpensive, but offer a large flow resistance.

Alternative solutions however can considerably reduce the pressure loss or even remove the need for a filter. As already anticipated in Chapter 2 some alternatives to bag filters are available.

Electrostatic precipitators

An effective filtering is realised by charging the particles and aerosols in the air stream and remove them by means of an electric field. The associated pressure loss is only 2 Pa. The advantage of electrostatic air filters is that they capture fine particles which are most harmful to human health.

The drawback of this system is that they let large particles pass and that

they have a high feed-in price and power consumption, which depends on the number of ionized particles in the air.

Apart from the energy use, they also produce ozone particles and Volatile Organic Compounds (VOC) which are harmful for the environment.

Alternative solution with no filters:
embedded culvert

Embedded culvert are definitely not a common solution and, often, they are not feasible due to underground space limitations. However, some examples can be found. In [22] an example of such solution is documented.

This consists of a 15 m long underground culvert where supply air is extracted: when air flows in the duct, the decrease of $>0.3 \mu\text{m}$ particles is 85% and 95% for larger particles. This completely remove the need for a filtering device. The duct is large enough to be passable for manual cleaning.

Recommendations for heat exchangers

- Reduced air speed increases the thermal efficiency of the heat exchangers and heating and cooling coils. In a low-speed systems, the dimension of the heat exchangers and the coils can be reduced, in turn reducing the pressure losses.
- When the heat exchanger is sufficiently efficient ($> 80\%$ efficiency) it might be possible to completely omit the inlet heating coil, therefore reducing the pressure loss. It is recommended to test this option with accurate energy calculations of the building.
- Using a bypass system allows to skip the heat exchanger when it is not in function. However, this solution is often impractical due to lack of space.
- Carefully consider if the heat exchanger is needed at all. If the supply temperature can be low, a heat exchanger or even an heating coil might not be necessary (see Diffuse Ceilings at Chapter 3.3.a

B.2| Heating/cooling coils and heat exchangers

The functions of heating and cooling elements, as well as of heat exchangers for heat recovery purposes have been explained in Chapter 2.

This paragraph shows few alternatives to the two traditional traditional solutions previously discussed.

Heat pipes

Heat pipes are heat recovery systems that consist of a working fluid, a casing and a wick structure. The pipe is divided into two sections, an evaporator side and a condenser side. On the evaporator side a fluid will evaporate as a result of the warm outgoing ventilation air. The incoming fresh air creates a cold side where the medium will condense. This causes a pressure difference through which the gas will flow in the middle of the pipe and heat transport will occur. The condensed medium will migrate back to the warm side through gravity or capillary forces across the wick structure. This system can be integrated into ventilation ducts because of its low flow resistance.

The pressure loss depends on the air velocity which is influenced by the size of the heat pipe, its placement and type of fins. The finned pipes provide heat transfer between air and medium in the pipe. Heat pipes have a higher efficiency at lower speeds. This is favorable for low-pressure systems where low ventilation speeds are intended.

For a thermal efficiency of 50% and an air velocity of 0.5 m/s the pressure

loss was around 1 Pa. If the heat pipe is more streamlined, the pressure drop can be even lower.

Higher efficiencies can be achieved if more banks of heat pipes were used, although with larger pressure losses. [23, 19]

Run around systems

Run around systems are systems in which a fluid absorbs heat from the incoming or outgoing air. A fluid in a loop is pumped around between the inter-linked heat exchangers, placed at the air inlet and the air outlet.

The heat exchanger at the outlet will recover and pass heat from the outgoing air to the fluid. The hot fluid is pumped to the inlet heat exchanger where it will transfer heat to the incoming air. The reverse cycle is also possible for cooling.

The research of Hviid and Svendsen [15] shows that by using two air-to-liquid heat exchangers, connected through a liquid loop, only a pressure loss of 0.74 Pa is achieved with a system efficiency of 75.6% [15].

Research by Davidsson, et al. [2] (2013) claims that a pressure loss of 1 Pa is possible with a system efficiency of 80%. A big advantage of this system is its flexibility in the placement of the heat exchangers since the supply and extract ducts don't necessarily need to be placed side by side.

Phase change materials

Phase change materials or PCM's are materials that can temporarily store heat or cold by changing phases. In

this way, extreme temperatures can be avoided. PCM's provide a reduced air flow rate to ensure thermal comfort by storing energy during the night and recovering it during the day. There are 3 different types of PCM's: organic, non-organic and inorganic eutectics. While PCM's are an effective way to recover heat without creating a pressure drop, the applications are limited in the field of ventilation. A low pressure drop is ensured because PCM's can be directly integrated into the building structure without creating a physical obstacle to the air flow. The University of Bournemouth has installed Two Monodraught Cool-phase systems for ventilative cooling with natural driving force and night ventilation. The PCM's filled with paraffin act like a thermal battery and will cool the incoming air before distributing it into the occupied zones [9].

Embedded ducts

Embedded ducts are central inlet channels located in the ground, connected to a building. A big advantage is that the incoming air supply is independent of the building. Its location can be chosen where the outdoor air quality is the highest and the outdoor noise pollution the least. A negative consequence is that once the channels have been constructed, they can no longer be modified. Energy saving is influenced by heat storage in the thermal mass surrounding the ducts. The incoming air can be cooled or heated passively. These bigger underground channels also provide initial filtering: large particles will drop due to low velocities and gravity forces. Embedded ducts also have drawbacks. First of all, during hot days, condensation can cause fungus to occur on the inner wall of the embedded duct. Secondly, the

construction costs are relatively high.

Cases with bypass or no heat exchanger/coils

There are certain situations where the heating coils or the heat exchanger can be avoided. When the heat exchanger is extremely efficient (e.g. above than 80%) and the climate is not too cold, the heating coil can be omitted, and the supply air is solely heated by the warmer exhaust air. In other situations, where the supply air temperature is sufficiently low (e.g. when diffuse ceilings are used, see Chapter 3.3.a) the heat exchanger (or both heat exchanger and heating coil) can also be avoided. When sufficient space is available, the ventilation system can be provided with a bypass option, so that during milder seasons the air is no longer forced through the heat exchanger but directly into the ductwork, considerably reducing the pressure loss.

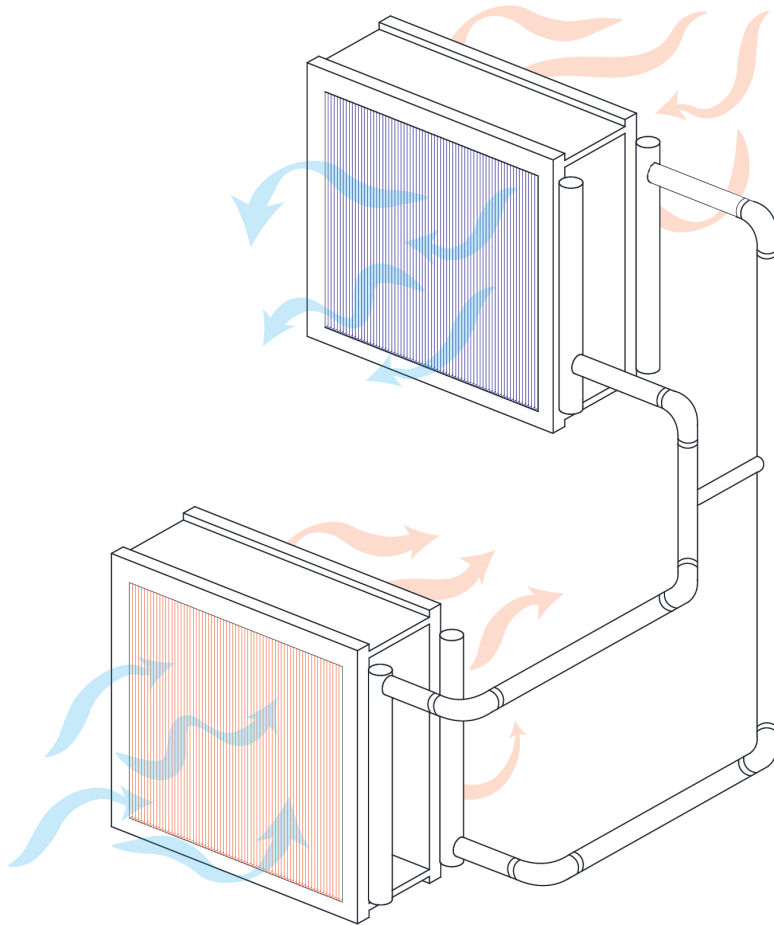


Figure B1. Scheme of a run-around heat exchanger

Recommendations for air inlets and outlets

- Keep inlet and exhaust ducts as short as possible.
- Locate air intakes and exhausts so as to prevent short-circuiting from exhaust to inlet
- Place inlets where the prevailing wind pressure is positive and the outlets where the prevailing wind pressure is negative.
- Avoid high-velocity jet stacks
- If high-velocity jet stacks are unavoidable, try to design to keep the pressure drop as low as possible (maximum 50 Pa) with low-pressure design options

B.3| Inlets and outlets

Typical outlets have a design pressure loss of 40 to 175 Pa [1, 14, 26] as discussed in Chapter 2. However,

increasing the area of the standard components 3 to 4 times, and therefore reducing the air speed, it is possible to obtain a pressure loss of 5 Pa, assuming that there are no wind effects that can cause a significantly increased pressure loss [20].

the placement of inlet and outlet components is important in order not to obtain negative wind effects.

The inlet terminal is preferably placed where the prevailing wind pressure is positive.

The exhaust terminal is best located at the place with a prevailing negative wind pressure [3]. Exhaust outlets should be designed to keep the pressure drop below 50 Pa [21], for this reason is it suggested to avoid high-velocity jet stacks.

When jet stacks are unavoidable and the above solutions are not viable, alternative stack designs are available with low pressure loss, as shown in Figure B3.

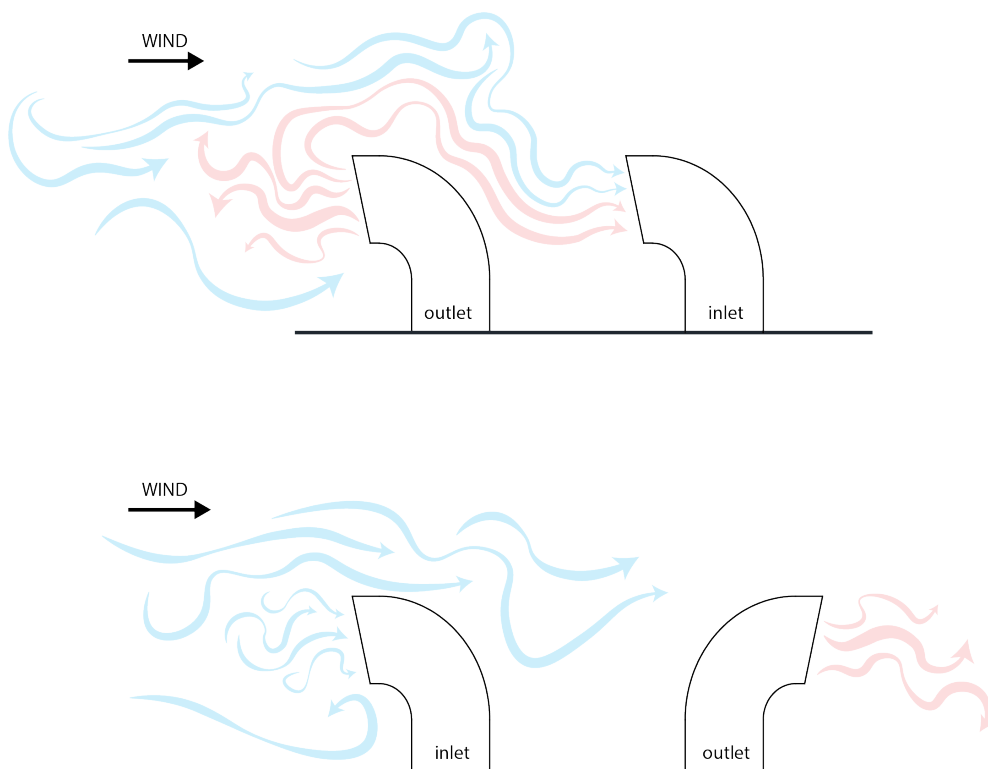


Figure B2. Top: wrong positioning of inlet and outlet. Bottom: correct positioning: the inlet faces the prevailing wind direction, while the outlet is directed downwind.

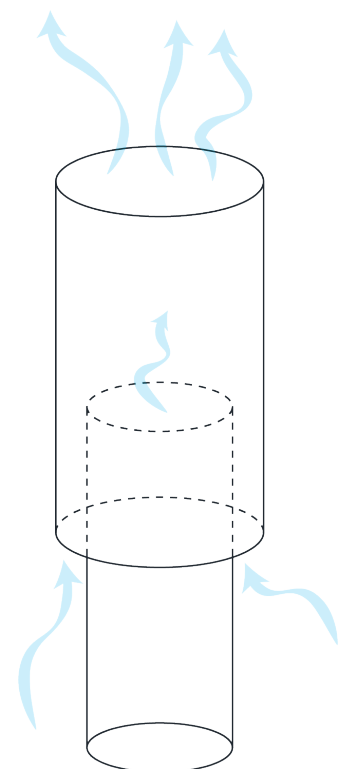


Figure B3. Alternative jet stack design

Recommendations for ductwork

- Design ductwork as early as possible in the project for optimal integration
- Use short ducts
- Reduce the number of twists and bends
- All dampers should be open along the critical path
- Dimension ducts so to achieve a pressure gradient of 0.8 to 1Pa/m
- Rigid-walled round ductwork combined with rubber gaskets is preferred over square and flexible ducting
- Bends are preferred above T-junctions
- Regularly inspect and clean supply and exhaust ducts
- Atria and stairwells can be used for distributing air instead of part of the ductwork.

B.4| Ductwork

As discussed in Chapter 2, the duct network is responsible of a considerable amount of the total pressure loss of the ventilation system. the following recommendations are some of the most common strategies for reducing the flow resistance of the air distribution system:

- the design of the ductwork should be taken into consideration as early as possible in the building design, possibly already during concept design when spaces are allocated, room height decided and the floor package drafted. In fact, the more the ductwork is integrated into the design, the more chances are there to achieve an efficient, low-pressure air transportation system, as well as the best aesthetical results;
- the ductwork should be designed as aerodynamically as possible. Few twists and bends, short duct lengths and a symmetrical design to reduce the need for air valves are essential. Along the critical path, all dampers

should be open.

- a pressure gradient of 0.8 to 1Pa/m in the ducts is advised b to determine the duct size, not just for energy saving purposes, but also for noise reduction [21, 18];
- when possible, increasing the duct size is advised: for instance, if a duct diameter of 200 mm is increased to 250 mm, the air velocity decreases by 35% and the pressure drop by 60%;
- rigid-walled round ductwork combined with rubber gaskets is preferred over square and flexible ducting to lower the pressure drop. Bends are preferred above T-junctions, to avoid pressure losses to exceed 5 Pa;
- regular inspections and cleaning of the ducts is a good practice for reducing the pressure drop: dust and dirt can infect increase the roughness of the ducts surface, which in turn increases the flow resistance along the length of the duct.

Recommendations for silencers

- The expected noise should be calculated during the design phase in order to select the best silencers.
- Select silencers that are as long as possible
- Keep the air speed as low as possible to reduce or avoid the need for silencers
- Duct silencers should have the same internal free area as the connecting ductwork
- Make use of inlet bell and outlet regain silencers at the fan with a maximum of 20 Pa pressure drop.
- Make use of optimized ductwork silencers which are as long as possible
- Avoid traditional rectangular silencers with baffles and splitters when possible.
- A low-pressure ventilation system have by itself a low noise level

B.5| Silencers

Silencers have the function of attenuating the noise at the source or at the receiver.

For this reason they are normally placed either centrally in the air handling unit or locally in the ductwork; they first ones are designed for reducing the fan noise, the second for reducing the flow-generated noise.

Traditional silencers can be quite bulky and can offer considerable flow resistance. For this reason, their selection or design should be optimized. It must be kept in mind that in a well designed, low-pressure, low-speed ventilation system the noise generation is per se lower than in a traditional system and the need for silencers is reduced.

AHU silencers

In a standard system, AHU silencers with baffles are used. These devices are certainly effective, but they offer a considerable flow resistance and thus increase the fan energy.

As an alternative, more advanced silencers with aerodynamic shapes and low flow resistance can be fit directly around the fan.

This is the case of the inlet bell silenc-

ers and the outlet regain silencers (Figure B4 left). The downside is that for achieving best performance, such devices should be custom designed and integrated into the AHU, which is costly. However, other mass-produced silencers are available with minimal inlet and outlet loss (see Figure B4 right).

Duct silencers

A second, more conventional type of silencers that can substitute traditional baffle systems are the ductwork AHU silencers. Despite their flow resistance is higher than custom-made inlet bell and the outlet regain silencers, they offer minimal inlet and outlet loss thanks to their aerodynamic shape and can be sized for a maximum pressure loss of 20 Pa. It is important that the duct silencer has the same internal free area as the connecting ductwork in order to minimize the flow resistance.

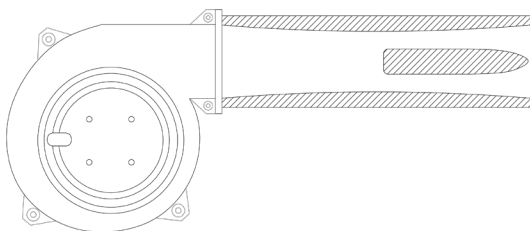
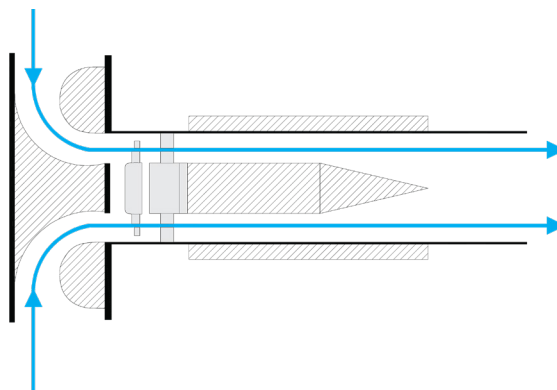


Figure B4. Left: centrifugal fan with outlet regain silencer. Right: axial fan with inlet-bell and outlet regain silencers



Recommendations for fans

- The cross-sectional area of the inlet duct should be between 92% and 112% of the fan inlet area
- Any kind of obstacles, e.g. dampers, should not be near the fan inlet
- The length of the inlet duct should be at least 3 times its (hydraulic) diameter. If this is not possible, square duct bends must be provided with turning vanes to prevent spin. In the case of round duct bends, the inner diameter of the bend must be at least as large as the duct diameter.
- Connect a straight channel with a length of at least 2.5 times the hydraulic diameter to spread the speed profile and to give static regain. This means higher static pressure but lower velocity pressure.
- If the dimensions of the outlet do not correspond to the dimensions of the distribution channel, a gradual transition must be provided.
- If bends are placed directly after the outlet, they must follow the recommendations in Figure B6

B.6| Grills and diffusers

In a good design, terminals should have a pressure drop of less than 30 Pa. Low-velocity supply terminals (particularly suited for displacement

ventilation) work with much lower pressure drop than high-velocity jet terminals (more suited for mixing ventilation).

B.7| Fan inlet and outlet – aerodynamic inefficiencies

It is important to calculate the pressure losses over the ventilation system as accurately as possible in order to choose the right fan, based on the fan curves. The aim is to function as close as possible to the peak efficiency.

A fan is chosen where the operating point is within 10% of the fan peak efficiency. For low-pressure systems

it is recommended to select efficient axial fans.

Fan inlets and outlets should be designed as aerodynamically as possible.

There are some basic principles that try to ensure a swirl-free symmetrical fully-developed velocity profile to avoid air spin at the inlet, so pressure loss can be limited [21].

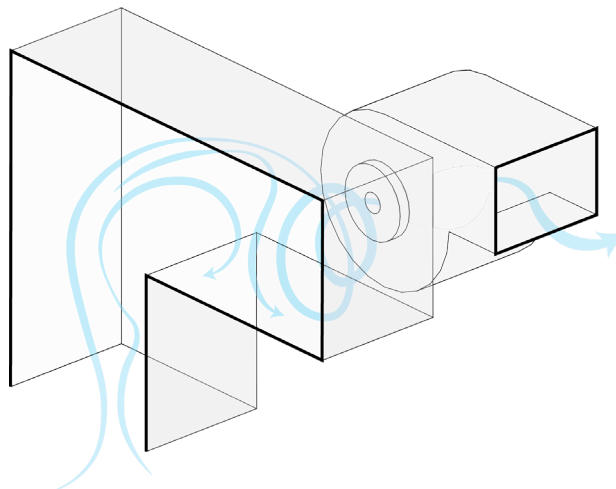
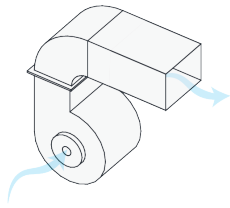


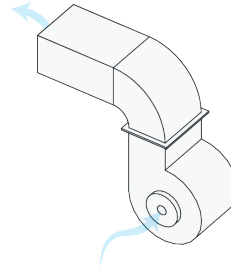
Figure B5. Example of poor design that generates a vortex rotating in the same direction as the fan. In order to reduce the swirl, turning vanes should be added in the bend.

Apart from the traditional duct networks there are lots of **alternative strategies** for distributing air in a building.

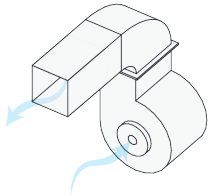
Several strategies allow for a very **low-pressure design**. For instance, elevated floors or false ceilings can be used for distributing air, as well as decentralised systems with multiple fans.



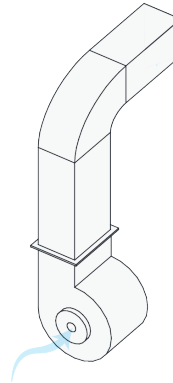
a) A bend following the rotation of fan-outlet swirl gives least loss



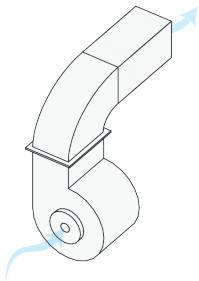
d) This is a poor solution that gives 10% worse efficiency compared to straight duct outlet (no bend)



b) A bend pointing to the same side as the fan intake gives little loss



e) If the bend in c) or d) is unavoidable, there should be a straight duct of a least 2.5 to 6 times that fan outlet diameter.



c) A bend pointing to the opposite side as the fan intake gives 5% worse efficiency compared to no bend

Figure B6. Dos and don'ts in the design of fan outlets

Bibliography

- [1] Blomsterberg Å. et al., "Design methods for ventilation systems in residential and commercial buildings," 2000.
- [2] Davidsson H., Bernardo R. and Hellström B. J. B., "Theoretical and experimental investigation of a heat exchanger suitable for a hybrid ventilation system," vol. 3, no. 1, pp. 18-38, 2013.
- [3] Delsante A. and Vik T. J. P. o. H. V., "Hybrid Ventilation: state of the art review," 2002.
- [4] Delsante A., Vik T.A., Hybrid Ventilation: state of the art review, IEA Energy Conservation in Buildings and Community Systems Annex 35 Hybrid Ventilation in New and Retrofitted Office Buildings, 2001.
- [5] Dokka T.H., Mysen M., Schild P.G. and Tjelflaat P.O., Bygningsintegrert ventilasjon – en veileder, Økobyggprogrammet for byggforsk and NTNU/SINTEF, Norway, 2003
- [6] Gunner A., Afshari A., Bergsøe N. C., Vorre A. and Hultmark G., "Energy savings and manifold supply ventilation systems," Journal of Building Engineering, vol. 7, pp. 71-77, 2016/09/01/ 2016.
- [7] Gunner A., Hultmark G., Vorre A., Afshari A. and Bergsøe N. C., "Energy-saving potential of a novel ventilation system with decentralised fans in an office building," Energy and Buildings, vol. 84, pp. 360-366, 2014/12/01/ 2014.
- [8] Heikkinen J., Heinonen J.S., Laine T., Liljeström K., Vuolle M., Performance simulation of hybrid ventilation concepts – IEA Annex 35, July 2002
- [9] Heiselberg P. K. and Kolokotroni M., "Ventilative Cooling: State-of-the-art review executive summary," pp. 104-105, 139 & 164-165, 2017.
- [10] Heiselberg P., Design of Natural and Hybrid Ventilation, Lecture Notes No. 005 Dept. of Civil Engineering, Aalborg University, 2006
- [11] Heiselberg, P. Principles of hybrid ventilation, 2002
- [12] Heiselberg, P., Murakami, S. and Roulet, C.–A. (eds): Ventilation of Large Spaces in Buildings – Analysis and Prediction Techniques, IEA Annex 26 Report, Department of Building Technology and Structural Engineering, Aalborg University, Denmark, 1998
- [13] https://www.ghdonline.org/uploads/2009-08-07_1130_Levin-NV_Mixed_Mode.pdf
- [14] Hvenegaard C. M., Drivsholm C., Jensen J. B., Lindholm D. and Mikkelsen D., Den lille blå om ventilation. Dansk Energi, 2007.
- [15] Hviid C.A. and Svendsen S., "Analytical and experimental analysis of a low-pressure heat exchanger suitable for passive ventilation," Energy and Buildings, vol. 43, no. 2, pp. 275-284, 2011/02/01/ 2011.
- [16] Hviid, C. A., & Svendsen, S. (2012). Wind- and stack-assisted mechanical ventilation with heat recovery and night cooling. Technical University of Denmark, Department of Civil Engineering.

- [17] Kim M., Baldini L., Energy analysis of a decentralized ventilation system compared with centralized ventilation systems in European climates: Based on review of analyses, Energy and Buildings 2016
- [18] Nilsson L. J., "Air-handling energy efficiency and design practices," Energy and Buildings, vol. 22, no. 1, pp. 1-13, 1995/03/01/ 1995.
- [19] Riffat S. B. and Gan G., "Determination of effectiveness of heat-pipe heat recovery for naturally-ventilated buildings," Applied Thermal Engineering, vol. 18, no. 3, pp. 121-130, 1998/03/01/ 1998.
- [20] S. Terkildsen and S. J. I. J. o. V. Svendsen, "Performance potential of mechanical ventilation systems with minimized pressure loss," International Journal of Ventilation, vol. 11, no. 4, pp. 367-380, 2013.
- [21] Schild P.G., Mysen M., Recommendations on Specific Fan Power and Fan System Efficiency, AIVC Technical note 65, 2009
- [22] Schild, P.G., 2001. An overview of Norwegian buildings with hybrid ventilation. In: anonymous (Ed.), Hyb-Vent Forum 01. IEA Annex 35
- [23] Shao L. and Riffat S. B., "Flow loss caused by heat pipes in natural ventilation stacks," Applied Thermal Engineering, vol. 17, no. 4, pp. 393-399, 1997/04/01/ 1997.
- [24] Terkildsen S., "Development of mechanical ventilation system with low energy consumption for renovation of buildings," 2013.
- [25] van der Aa A., Heiselberg P., de Gids W., When the EPR hits the fan, or...the killing of the fan energy, 40th AIVC - 8th TightVent - 6th venticool Conference - Ghent, Belgium - 15-16 October 2019
- [26] Wouters P., Heijmans N., Delmotte C., Vandaele L., Classification Of Hybrid Ventilation Concepts, Belgian Building Research Institute
- [27] Zhang C., Yu T., Heiselberg P.K., Pomianowski M.Z., Nielsen, P.V., Diffuse Ceiling Ventilation - Design Guide, DCE Technical Report No. 217, Aalborg University Department of Civil Engineering Indoor Environmental Engineering Research Group, 2016
- [28] <https://bronconsult.org/language/en/research/the-earth-wind-fire-concept/>
- [29] https://en.wikipedia.org/wiki/Demand_controlled_ventilation

This publication is a compendium of many viable design solutions for reducing the fan energy in ventilation systems of new and existing buildings. The authors want to provide a brief and inspirational handbook for different kinds of professionals in the building industry, also without prior knowledge of ventilation systems.

The text is addressed to architects, designers, engineers and real-estate developers who want to know more about the topic of low-pressure ventilation. This booklet is the result of a collaboration between ABT and the Faculty of Applied Engineering and Design Sciences of University of Antwerp.

The authors hope that by disseminating this information, the design of low-pressure systems will become common practice and together we will work on integrated, healthy and sustainable buildings.

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The logo for ABT, consisting of the lowercase letters 'abt' in a bold, blue, sans-serif font.The logo for the University of Antwerp, featuring a stylized 'U' in red and blue, followed by the text 'University of Antwerp' in a blue, sans-serif font.